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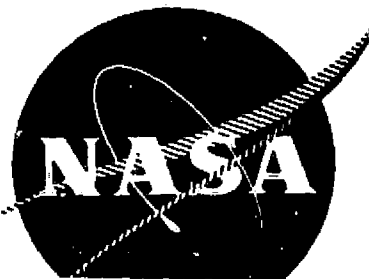
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FINAL REPORT

CdS SOLAR CELL DEVELOPMENT

by

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16. Abstract

Studies were conducted on the effects of variations in manufacturing processes on cell performance, with particular attention to temperature during evaporation and to temperature and time exposure in air after barriering. In general, the existence of broad optimums was verified. A variety of cover plastics were evaluated and a method of very rapid heat bonding on FEP Teflon was developed. Studies were conducted on interlayer surfaces using X-ray diffraction and SEM techniques. Performance of cells was definitely correlated to surface characteristics of the silver Pyre ML paint and the further effect of this surface on alloying of the zinc layer with the silver was investigated. Variations of the grid structure were evaluated. Stability testing was continued for the 5th year under conditions of dry shelf, vacuum, and moisture storage.

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FOREWORD

TABLE OF CONTENTS

ABSTRACT

Studies were conducted on the effects of variations in manufacturing processes on cell performance, with particular attention to temperature during evaporation and to temperature and time exposure in air after barriering. In general, the existence of broad optimums was verified. A variety of cover plastics were evaluated and a method of very rapid heat bonding on FEP Teflon was developed. Studies were conducted on inter-layer surfaces using X-ray diffraction and SEM techniques. Performance of cells was definitely correlated to surface characteristics of the silver Pyre ML paint and the further effect of this surface on alloying of the zinc layer with the silver was investigated. Variations of the grid structure were evaluated. Stability testing was continued for the 5th year under conditions of dry shelf, vacuum, and moisture storage.

LIST OF ILLUSTRATIONS

LIST OF TABLES

x

SUMMARY

A total of 672 standard process cells meeting Class 1 requirements were produced under this contract   By definition Class 1 cells have a minimum AM0-25°C efficiency of 2.8%, a minimum fill factor of 68.5% and an SCC at 60°C that is no lower than 2% below the 25° SCC value.   Monthly effort on cell production was limited by contract.   Fill factor was the controlling limitation in yields.

Long term stability testing has continued on three separate tests, dry shelf storage, moisture storage, and 100°C vacuum storage.   The average performance of cells on dry shelf storage fabricated in 1966-1967 has remained within 10% of initial performance.   The averages of 1968, 1969, and 1970 cells have remained within 5% of initial performance.   The moisture storage test (80% RH, room temperature) was more severe.   Efficiencies dropped fairly steadily to between 75% and 80% of initial value in 25 to 30 months.   Cells that dropped below 75% were removed from the test and analyzed.   It is apparent that the 1970 cells, like the 1967 cells, failed at a greater initial rate than the rest.   The 100°C high vacuum storage test, instituted as an accelerated space test, is quite severe.   None of the 1966 cells and only one of the 1967 cells retained 75% of initial output.   Most cells hold up well for 24 months.   Many, but not all, drop below the 75% figure after 28-30 months on test.   1968 cells retained an average of 93% of their output after 12 months and 91% after 24 months.   1969 cells averaged 104% of output after 12 months and 91% after 18 months.   1970 cells averaged 100% after 7 months.   Analysis of the type of degradation present on the three tests, as well as recovery experiments on failed cells, indicate that at least two separate degradation mechanisms appear to be present.   One that apparently affects the SCC, seems to be dominant on the dry and wet shelf tests while the other, which apparently affects the fill factor, appears to be dominant on the 100° C vacuum test.

Alternative methods of controlling temperature of the substrate during evaporation were investigated.   In one series of experiments power was pulsed to the heaters in accordance with a predetermined program.   With a fairly complex program a good degree of temperature uniformity was achieved.   Cells fabricated from substrates whose temperatures were so controlled during CdS evaporation were not significantly different from standard process substrates cells fabricated from substrates whose temperatures were thermocouple controlled.   Attempts at heating substrates conductively during CdS evaporation were unsuccessful.   A series of substrates were evaporated under thermocouple control at temperatures ranging from 180°C to 300°C in 20°C increments.   Cell outputs were effected only at the two extremes.   It was concluded that a broad optimum exists from 200°C to 260°C.

A procedure for successfully bonding FEP Teflon to cells without the associated heat damage was developed.   This involved special fixturing of the laminating press so that heat exposure was less than 30 seconds.   Teflon covered cells laminated by this process showed more output after lamination than before, with some cells showing an efficiency as high as 5.2% AM0.   Twenty days after fabrication, a group of 24 cells showed an average efficiency of 4.53% AM0-25°C

and an average fill of 64.8%. Resistance to humidity proved poorer than Kapton covered cells. Three different weatherable polyesters showed promise as cell covers because of more favorable UV cut off. Aclar 33C was also tried as cover. The latter is especially attractive because of somewhat lower bonding temperature and vastly superior humidity protection. It was found that either the Aclar 33C or FEP Teflon could be used as a bonding film for Kapton.

Cells with FEP Teflon covers, and cells with Kapton covers were exposed to controlled environments at a variety of temperatures and humidities in air and in nitrogen. The higher humidities proved most destructive, with Kapton covers showing better protection than Teflon.

A number of cells were constructed with grids having line densities of 50, 70, and 80 lines per inch compared to the standard 60 lines. No significant gain in performance was noted by going to the finer structures.

Surface studies of the various layers of the cell were carried out using the scanning electron microscope and X-ray diffraction techniques. Marked differences were found in the surface characteristics of roll coated as compared to sprayed substrates and the effect of these differences was apparent in all subsequent layers of the cells. The varying degree with which the zinc alloyed with the silver correlated with the surface characteristics. The SCC of cells was shown to increase as the thickness of the zinc interlayer was increased.

Extensive data was accumulated on the combined effects of time, heat, and oxygen on freshly barriered substrates. The data has been forwarded to NASA for computer analysis.

INTRODUCTION

This report covers work done on the continuation of a program that has been supported by NASA since 1963 and was aimed at developing the thin film cadmium sulfide solar cell to a point where it would be useful in space applications. Pilot production of existing design cells continued throughout the year although hampered by a varying production yield. Identification of the causes of the varying yield was the object of much effort during the entire period. The efforts in improving cell performance were divided between studies on the effects of variations in existing cell fabrication processes and the substitution of new materials or new processes for existing ones. The cell stability testing program was extended into the fifth year.

CELL FABRICATION

Standard Cell Production. - The standard process fabrication line produced a total of 672 Class 1 quality cells during the contractual period, where Class 1 quality is defined as a minimum AM0 efficiency of 2.8%, a minimum fill factor of 68.5% and an SCC at 60°C, that is no lower than 2% below the 25°C SCC. As will be discussed more fully later, a widely fluctuating production yield prevented meeting the required cell quota. The averages of the AM0-25°C performance parameters of the 672 Class 1 cells, as well as their standard deviations are shown in Table I.

For purposes of comparison the corresponding averages of the 1969 Class 1 cells are also shown. As can be seen the average OCV is approximately the same, the average SCC and maximum power are slightly higher while the average fill is slightly lower.

The averages and standard deviations of the AM0-60°C performance parameters are shown in Table II.

The OCV and maximum power temperature coefficients, based on the averages at these two temperatures, are -1.40 mV/°C and -1.09 mW/°C respectively. The OCV coefficient is somewhat lower than the -1.60 mV/°C that has been reported earlier, and is also lower than the -1.49 mV/°C reported a year ago for 1969's cells but the -1.09 mW/°C maximum power coefficient is in

1

Table I. Average AM0-25°C Performance Parameters of
672 Kapton Covered Class 1 Cells

Parameter	Average	Standard Deviation	1969 Average (534 Cells)
OCV	.472 V	.005 V	.469 V
SCC	.798 A	.030 A	.761 A
P_{max}	.260 W	.009 W	.250 W
Fill	69.3 %	0.3 %	70.1 %
Eff.	3.39 % (Based on above P_{max})		3.26 %

Table II. Average AM0-60°C Performance Parameters of
672 Kapton Covered Class 1 Cells

Parameter	Average	Standard Deviation
OCV	.423 V	.005 V
SCC	.799 A	.027 A
P_{max}	.222 W	.008 W
Fill	66.0 %	0.5 %
Eff.	2.90 % (Based on above P_{max})	

2

line with previously observed values, e. g. , -1.14 mW/°C for 1969's cells. The reason for the smaller OCV coefficient is unknown. Periodic calibration of the temperature of the mounting block in the cell tester has assured that the accuracy remained within the specified ± 3%.

Cell performance at low light levels, e. g. , less than 1/100 AMO, has long been thought of perhaps providing some prediction of cell stability. The caliber of low light level performance is determined more by the shunt resistance of the cell than by any of its other parameters. However, neither cell performance at low light levels, nor the limiting value of shunt resistance as light intensity is decreased can be determined from AMO-25°C performance,[1] hence each cell must be individually tested under reduced light intensity. The process of final inspection and testing to which all potential Class 1 cells are subjected includes curve tracing at 1/100 AMO-25°C and each month the ten best and ten worst performing cells, based somewhat arbitrarily on the appearance of the squareness of their 1/100 AMO curve, are tabulated so that cells can be selected for environmental testing according to their low light level performance. Table III lists the averages and standard deviations of 90 cells, selected as the 10 best, from nine of the production months in which Class 1 cell yields were sufficiently large to provide both good and poor performance at 1/100 AMO-25°C.

Table III.   Average 0.01 AMO-25°C Performance Parameters
of 90 Selected Kapton Covered Cells

Parameters	Average	Standard Deviation
OCV	.357 V	.009 V
SCC	8.02 mA	0.67 mA
P_{max}	1.97 mW	0.15 mW
Fill	69.0 %	1.0 %
Eff.	2.58 % (Based on above P_{max})	

These average parameters are indicative of the best performance that can be reasonably expected from standard process Class 1 cells at this light intensity. The performance of the remainder of the 672 cells, while not tabulated, ranged as low as completely shorted on a few occasions. No results from environmental tests are available as yet to determine if a correlation between cell stability and initial low light level performance exists.

Quality Control and Production Yields. - During the contractual period the standard process fabrication line delivered a total of 3116 completed cells to final testing and inspection. Of these 672, or 21.6%, qualified as Class 1 cells. The remainder were rejected for one or more of the following five reasons: a fill factor below 68.5%, an efficiency below 2.8%; a short or abnormally low resistance between the cell terminals; failure on the 60°C test, or cosmetic flaws such as broken grid wires, voids in the cover plastic epoxy, foreign

3

inclusions under the cover plastic, torn tabs, etc. Table IV shows how each month's production of cells during the year was classified. Classification is by the first observed cause for rejection, a rejected cell receiving no further inspection.

Table IV.   Monthly Classifications of Completed Cells in
Final Testing and Inspection

Month	Delivered to Final Inspection	Low Fill	Class 1	Low Efficiency	Shorted	Cosmetic	60°C Test
1	178	89	--	89	--	--	--
2	202	202	--	--	--	--	--
3	322	184	52	17	2	49	18
4	192	73	51	60	--	8	--
5	289	110	124	51	--	1	3
6	387	231	12	26	17	1	3
7	315	314	38	38	25	--	--
8	210	108	45	50	5	2	--
9	464	351	65	22	25	1	--
10	200	97	91	2	10	--	--
11	259	124	113	7	7	4	4
12	198	101	81	10	3	--	3
Total	3116	1884	672	372	94	66	28
Percent	100	60.5	21.6	11.9	3.0	2.1	0.9

It is obvious that production yields varied considerably from month-to-month; it is not obvious that the yields varied just as widely within most months as well. This variation in yields, or the lack of fabrication reproducibility which is its cause, has historically been the principal deterrent to the development of an acceptable thin film solar cell. Much time and effort have been expended in attempts to isolate the cause or causes of these variations in cell performance and the results of these efforts indicate that two procedures in the cell fabrication process appear to be more responsible for the observed irreproducibility than the remainder of the process taken as a whole. These areas will become apparent as the discussion proceeds.

Table V shows how the 2444 rejected cells were classified.

Table V.   Classification of Rejected Cells

Low Fill	77.1%
Low Efficiency	15.2
Shorted	3.9
Cosmetic	2.7
60°C Test	1.1

The main cause of cell rejection was obviously the inability to meet the 68. 5% minimum fill factor requirement. The elimination, or a significant reduction of this category would have easily allowed meeting the monthly production quotas. But more important, a clear understanding of the resultant effect on fill specifically assignable to each fabrication operation would probably have resulted in a more significant contribution in cell performance, as well as fabrication uniformity, than any other technological advance.

It must be noted, however, that most of the cells rejected for low fill were not significantly below the required 68. 5%. In fact, this was one of the difficulties experienced in attempting to correct the problem, since isolating the cause of a fill only slightly lower than required was much more difficult than identifying the cause of a fill significantly below specifications. Table VI shows how the average fill of all completed cells sent to final testing varied during the last five production months.

Table VI.   Monthly Values of Average Fill of All Completed
Cells Sent to Final Testing

Month	Mean Fill	Standard Deviation
8	67. 4	2. 5
9	66. 1	2. 0
10	67. 5	2. 0
11	67. 1	2. 4
12	67. 7	1. 8

Poor fill in the past had usually been traced to either an excessively high series resistance or to a poor shunt resistance. Both of these possibilities were thoroughly considered as soon as low fill became a problem. An accurate determination of these cell parameters is a lengthy process and is unsuitable for production use; however, at a sacrifice in accuracy, these resistances can be quickly determined from the slope of the I-V characteristic at its intersection with the voltage and current axes. The shunt resistance appeared to be at the same level that it has been for several years, i.e., in the 10 to 20 ohm range. The series resistance, however, did appear somewhat greater than normal. A series resistance of around 0. 07 ohms had been considered fairly typical for Class 1 cells, and values somewhat greater appeared to be present among current cells. The series resistances of three separate groups of cells were compared: 51 August, 1970 Class 1 cells; 61 August, 1970, reject cells; and 44 August, 1969 reject cells. Table VII shows the results.

Table VII.   Comparison of Series Resistance of Three Groups of Cells

	Average Series Resistance	Standard Deviation
61 August 1970 reject cells	0. 100	. 018
51 August 1970 Class 1 cells	0. 080	. 009
44 August 1969 reject cells	0. 077	. 009

These results indicated that indeed the series resistance of current production reject cells was significantly greater than either that of current Class 1 cells or reject cells from a year earlier. The fact that current Class 1 cells had a lower series resistance than did the reject cells indicated that the fabrication process was capable of producing low resistance cells, but for some unknown reason high series resistance cells were also being produced quite regularly. Since the 1969 rejected cells also had a lower resistance, it appeared that the source of high resistance was a recent occurrence. A fluctuating series resistance was of course puzzling since all cells are ostensibly fabricated in the same manner. Obviously some parameter in the process was varying and its identification was the object of an intensive effort.

The series resistance presented by a cell is the sum of the contributions of a number of smaller resistances, any one of which could have been the source of the observed increase. Of immediate suspicion were those that in the past had been known to cause excessive series resistance problems. These included the substrate, the CdS film, the barrier layer and the grid.

Routine inspection measurements on CdS film resistivity, while indicating that variations were present, were not significantly different from previous measurements. Since normal values of OCV and SCC appeared present in production cells, the junction region was presumed normal. The grid itself has not been known to cause a high series resistance but problems with the contact between the grid and the barrier layer have occasionally done so, particularly if the cover plastic epoxy was overly thick, which apparently caused loosening of the grid epoxy during the cover plastic lamination cycle. Careful inspection and control of the parameters involved quickly ruled this possibility out. Hence the prime areas suspected were the substrate and its contact to the CdS film, and the barrier layer.

The barrier layer was particularly suspected because most cells appeared to require a several week adjustment period after fabrication before they reached their maximum performance. Such behavior in the past has been attributed to an incomplete barrier formation process, so quite naturally this fabrication step was carefully studied for any signs of deviations from the standard process fabrication procedure.

In addition, a number of carefully controlled process variations were introduced as part of an overall program to isolate the cause of the suspected incomplete barrier formation process and hopefully, the increased series resistance as well.

The nature of this adjustment period resembled an aging process in that the most significant change that usually occurred was an increase in fill. As a result, many cells initially rejected for low fill increased in fill to above the required 68.5%, warranting reclassification as Class 1 cells. Table VIII shows the effects of this adjustment period on 37 cells from the 11th production month that had initially been rejected for low fill. The initial AM0-25°C performance parameters were obtained immediately after the fabrication process had been completed, and the second set was obtained after the cells had been exposed to normal room atmosphere for a period of two weeks.

6

Table VIII. Effect of Two Week Adjustment Period on
AM0-25°C Performance of 37 Rejected Cells

	Initial Coverage Parameters	Average Parameters Two Weeks Later
OCV	.471	.475 V
SCC	.862	.845 A
P_{max}	.272	.277 W
Fill	67.2	68.9 %
Series Resistance	.083	.077 Ω
Eff. (Based on above P_{max})	3.55	3.61 %

The significant observable changes were a decrease in the SCC and series
resistance in addition to the increase in fill and a slight increase in maximum
power. The OCV remained essentially constant. It is tempting to conclude
that the 7% decrease in series resistance was responsible for the increase in
fill. However, the change in SCC is in the wrong direction to support this
since a decrease in series resistance ought to be accompanied by an increase
in SCC. It is also suspected that the change in series resistance is simply too
small to be detected by the method employed, hence the reported change is
open to doubt. The fact that the maximum power increased while the SCC
decreased results mathematically in the increase in fill. The mechanism
responsible for the loss of SCC while the maximum power increased is unknown,
but is thought to be associated with the incomplete barrier formation process.

In addition to observing the barrier formation process for any signs of
deviations from the standard process fabrication procedure, a number of care-
fully controlled process variations were introduced as part of an overall
program to isolate the cause of the suspected incomplete barrier formation
process as well as the increase in series resistance. Housekeeping activities
in the area were made more stringent and several improvements were incorporated
into the process where they were clearly needed. For example, the procedure
for mounting CdS films onto the dip cylinders was mechanized in order to
reduce their handling which was known to cause film cracking and subsequent
barrier layer shorting. The method of masking the CdS film for barrier dipping
was also modified so that the possibility of trapping etch and barrier solutions
in small pockets formed by the masking tape was reduced. A prerinse of the
CdS film in distilled water just prior to the acid etch was also evaluated, but
no differences were found attributable to it. A more thorough rinse was
introduced following the barrier dip by the installation of an immersion rinse
in addition to the spray rinse already in use. However, no differences were
found traceable to its presence.

One area of the barrier formation process that has long been suspected
of being a major determinant of cell performance and, hence, being partly
responsible for the ever-present production non-uniformity, is the effect of

7

exposing the newly formed barrier layer to the atmosphere. The fact that the two minute heat treatment at 250°C that follows barrier dipping must be done in the presence of air rather than in vacuum or in an inert atmosphere indicates that exposure to the atmosphere is required before the cell shows normal performance. It has also been observed, but not consistently, that a long-term exposure to room air at room temperature can be substituted for the two-minute 250°C air bake. Hence, it appears that exposure to some constituent of room air is a necessity before full operation of the cell can be realized. But the optimum exposure time and temperature, the point in the fabrication process where it is most beneficial, in addition to the identity of the specie, all remain unknown. Since all the cover plastics that have been used in the past are permeable to atmospheric constituents to some degree, this interaction undoubtedly continues for some time after the cell has been covered. The adjustment period that has been experienced at various times throughout the life of the project, in addition to the present, is very probably connected with this mechanism.

The CuCl powder that is used in the preparation of the barrier solution was also a prime suspect at one time, particularly after the preliminary results of a correlation experiment between CuCl lot number and cell performance became known. CuCl powder is purchased in 10 pound lots; and while it has been suspected of contributing to variations in cell performance at various times throughout the life of the project, no correlation has ever been established. A thorough study in which three different lots were used in rotation was undertaken and at first, when the sample sizes were relatively small, it appeared that a correlation did exist. However, as the sample sizes increased, the correlation gradually decreased and eventually disappeared.

One reason that the initial results indicated a correlation existed was that cell performance is grouped by substrate. That is one of the few correlations that has been positively shown to exist: that the nine cells from the same substrate perform relatively the same. While exceptions frequently occur, in general cells from the same substrate show a greater similarity in performance than do cells grouped by any other means, such as evaporation cycle, barrier formation lot, lamination cycle, etc. Hence, if a cell sample size is small enough to include only those from a few substrates, an erroneous conclusion can be easily formed.

This grouping of performance by substrate has obviously directed much of the search for the source of variations in cell performance to those fabrication processes in which the nine cell substrate is still intact, i. e., prior to the gridding process. The substrate preparation process is the other prime suspect for a number of reasons, including the rather consistent difference in performance observed between roll-coated prepared substrates and standard process sprayed substrates. Studies in which the apparent increase in cell series resistance was connected with an increase in the substrate resistance will be fully discussed in the section of the report dealing with substrate investigations. However, it can be pointed out here that the results of those studies indicate that substrate resistance does change as a result of high temperature

processing in subsequent fabrication steps, particularly the CdS evaporation cycle where the substrate is raised to a temperature of 220° C. Even though the substrate resistance is initially within the specified limits, zinc plating and the subsequent alloying of the zinc and silver during later elevated temperature processing raise the substrate resistance significantly, which could very easily contribute to the observed increase in series resistance. It was shown that roll-coated substrates are more stable[7] and consistent in performance but the difference in structure between the two types of substrates that accounted for this difference in performance was never clearly identified.

Hence, these two problem areas, the effect of exposure of the barrier layer to various gases, and the manner in which substrate preparation affects cell performance, will have to be resolved before an acceptable thin film solar cell can be developed. There are also an additional number of problems that will probably have to be considered; but until the mechanism by which these two process steps are related to ultimate cell performance is resolved, production non-uniformity and adjustments in initial cell performance will undoubtedly always be present.

CELL STABILITY

One of the major tasks of the present as well as previous contractual efforts has been the characterization of the stability of cell output on three separate environmental tests: storage in a desiccated atmosphere, high humidity room temperature storage, and 100° C vacuum storage. Each month beginning in 1966 with Contract No. NAS3-8502, several representative cells from the current production period were entered into each of the three tests. At the same time, all cells already on test were removed for performance testing, those manufactured prior to 1969 under AM1 conditions and those after 1969 under AM0 conditions.

Maintaining constant environments over the time periods involved, approaching five years for the case of 1966 cells, has not been too difficult for the dry atmosphere and the high humidity storage tests; however, maintaining the 100° C vacuum environment was more difficult. During 1968 the test had to be temporarily suspended for three months while the vacuum system was completely overhauled. Of even greater significance is the fact that cell testing conditions have changed somewhat over the five-year period. Initially, 500 W internally reflecting photoflood lamps were used as the light sources in the illuminated test assembly. In order to minimize the effect of envelope darkening, the lamps were used for only a third of their nominal six-hour life. This necessitated frequent replacement which made maintenance of uniform intensity and spectral calibration difficult. In 1968 the entire test assembly was replaced, more stable 650 W quartz-envelope tungsten-iodide lamps replacing the troublesome photoflood lamps. The effect of the resultant spectral shift on cell performance was not immediately apparent. However, it must be recognized that cells on long-term storage were no longer being tested under the initial conditions. At about the same time, the electronic load was also replaced with a unit of more advanced design, representing another perturbation from the initial test conditions. However, since no significant differences were apparent in the comparison of performance of cells tested with both illuminated test assemblies after thorough calibration, it will be assumed that the test conditions have remained constant in the data to be reported.

All cells reported here are of the same basic construction, i. e., standard process fabrication which includes the metallized plastic substrate and gold plated copper mesh grids attached to the barrier layer with a conductive gold epoxy. The cells are covered with 1 mil Mylar*prior to mid-1967 and 1 mil Kapton*since then. Both types of covers are attached with a transparent epoxy. Cells with covers other than Mylar or Kapton are considered nonstandard process and their test results are reported in the appropriate section on experimental cells.

*Trademark of E. I. duPont De Nemours & Co. Inc.

Dry Shelf Storage Stability. - Room temperature dry shelf storage represents stability testing under almost ideal conditions. Little or no degradation is expected since those degradation mechanisms that are reasonably expected to be present are temperature dependent, such as diffusion or alloying processes, and at room temperature should have negligible effects.

The facility simply consists of a commercially available laboratory type desiccator, charged with a chemical desiccant. While not in complete darkness, the cells receive a negligible amount of light since most of the room light that is incident on the cells through the desiccator walls is inconsequential because the cells are stored stacked together.

Tables IX through XIII show the actual and relative efficiencies of all cells on dry shelf storage by year of manufacture. The average relative efficiencies are shown at the bottom of each column, as well as the standard deviation for that column where it is thought helpful. Figure 1 shows plots of the average relative efficiency by year of manufacture.

The large fluctuations make interpretation of the data difficult. It does appear, however, that a very gradual downward trend is superimposed on the fluctuations, and is particularly evident in the 1966 and 1967 cells. But Table IX, which lists the history of the 1966 cells, indicates that cells D364F and D391B still show efficiencies that exceed their initial values after 55 months on test. Hence the gradual downward trend cannot be assumed to be an intrinsic degradation mechanism of the cell and probably reflects some fabrication problem. In fact, since there are no fundamental differences in cell construction from one year to the next any differences that appear in these stability data by year of manufacture probably reflect fluctuations in the degree of control over the fabrication process.

Figure 2 shows plots of the average relative efficiency by year of manufacture, all on the same time scale. It is apparent that the curves of the later cells, i. e. , 1969 and 1970, are less violently fluctuating than the curves of the earlier cells. This probably reflects an increasing degree of control over some part of the fabrication process. The standard deviations of the relative efficiency distributions, which are periodically listed among the tabulations in Tables IX through XIII, also indicate an increasing degree of process control by showing an increasing uniformity of performance stability.

No cell has ever been removed from the dry shelf storage test because of cell failure, defined as a decrease in output power to less than 75% of its initial value. All of the cells that showed significant degradation, >5% reduction in maximum power, also showed a reduction in relative SCC that was generally numerically equal to the reduction in relative output power. The 1966 and 1967 cells are of interest since no fill factor requirement had yet been incorporated into cell specifications at that time, permitting a wide range of fills among the cells on test. No apparent correlation could be found

11

Table IX. Actual and Relative AM1 Efficiencies of 1966 Cells on Dry Shelf Storage

Cell No.					Months on Test							
	0	5	10	15	20	25	30	35	40	45	50	55
D289D	5.4/100	5.0/93	4.8/89	4.9/91	4.6/85	4.6/85	4.5/83	4.8/89	4.5/83	--	4.7/87	4.7/87
D292D	5.3/100	5.0/94	4.8/91	5.0/94	4.5/85	4.6/87	4.6/87	4.8/91	4.8/91	--	4.7/89	4.6/87
D396B	4.9/100	4.4/90	4.3/88	4.5/92	4.1/84	4.2/86	4.1/84	4.3/88	4.1/84	--	4.2/86	4.1/84
D306D	5.6/100	5.0/90	4.9/88	5.0/89	4.8/86	4.8/86	4.6/82	5.0/89	5.0/89	--	4.8/86	4.7/84
D315A	5.6/100	5.2/93	5.3/95	5.2/93	4.7/84	4.8/86	5.0/89	5.2/93	5.0/89	--	4.9/88	4.9/88
D336D	4.6/100	4.5/98	4.2/91	4.4/96	4.3/94	4.1/89	3.8/83	4.3/94	4.3/94	--	4.2/91	4.1/89
D355C	5.1/100	5.3/104	5.3/104	5.4/106	--	5.0/98	4.8/94	5.1/100	5.1/100	--	4.9/96	5.0/98
D364F	4.0/100	4.0/100	4.3/108	4.5/112	--	4.2/105	4.1/102	4.3/108	4.3/108	--	4.2/105	4.2/105
D375C	4.5/100	4.6/102	4.4/98	4.4/98	4.0/89	4.1/91	--	4.3/96	4.4/98	--	4.2/93	4.2/93
D385B	5.0/100	5.0/100	5.1/102	4.8/96	4.8/96	--	4.8/96	4.7/98	5.0/100	--	4.8/96	4.8/96
D386E	5.0/100	5.2/104	5.2/104	5.0/100	4.8/96	4.9/98	--	5.1/102	5.1/102	--	5.0/100	4.9/98
D391B	4.5/100	5.1/113	5.0/111	4.8/107	4.8/107	4.6/102	4.7/104	4.9/109	5.0/111	--	4.8/107	4.8/107
D395C	4.2/100	4.3/102	4.1/98	4.0/95	4.0/95	4.0/95	4.0/95	4.2/100	4.2/100	--	4.1/98	4.1/98
D403B	4.6/100	4.8/104	4.6/100	4.4/96	4.3/94	4.4/96	4.4/96	4.4/96	4.5/98	--	4.4/96	4.3/93
D410B	4.9/100	--	4.6/94	4.5/92	--	4.2/86	4.4/90	4.5/92	4.3/88	4.4/90		
Ave.	(100)	99	97	97	91	92	91	96	96	--	94	93
Standard Deviation		6.3		6.3			7.0		7.6			7.0

Table X. Actual and Relative AM1 Efficiencies of 1967 Cells on Dry Shelf Storage

Cell No.	Months on Test												
	0	4	8	12	16	20	24	28	32	36	40	44	48
D513E	5.1/100	4.8/94	4.6/90	4.7/92	--	4.6/90	--	4.9/96	4.5/88	4.7/92	4.7/92	--	4.7/92
D522E	4.7/100	4.5/96	4.7/100	4.4/93	--	4.3/92	--	4.6/98	4.4/94	4.5/96	4.5/96	--	4.4/94
D551E	4.7/100	4.7/100	4.5/96	4.5/96	4.5/96	4.4/94	4.6/98	4.7/100	4.7/100	--	4.6/98	4.6/98	
D521F	4.4/100	4.4/100	--	4.4/100	4.5/102	4.2/96	4.4/100	4.6/105	4.6/105	4.6/105	--	--	4.5/102
D563A	4.8/100	4.6/96	4.5/94	4.4/92	4.4/92	4.2/88	4.4/92	--	4.6/96	--	4.5/94	4.4/92	
D579B	5.0/100	4.7/94	9.4/88	4.4/88	4.5/90	4.4/88	4.5/90	--	4.7/94	--	4.5/90	4.5/90	
D583C	5.0/100	4.8/96	4.4/88	4.5/90	4.5/90	4.6/92	4.6/92	--	4.9/98	--	4.6/92	4.7/94	
N14B2	5.1/100	4.7/92	4.6/90	4.5/88	4.6/90	4.6/90	4.6/90	--	4.9/96	--	4.7/92	4.6/90	
N20B1	5.1/100	4.7/92	4.6/90	4.6/90	4.6/90	4.6/90	4.6/90	--	4 9/96	--	4.6/90	4.6/90	
N31BK4	4.2/100	4.0/95	3.8/91	3.8/91	3.7/88	3.6/86	3.8/91	--	3.9/93	--	3.8/91	3.8/91	
N35B3	5.0/100	4.9/98	4.6/92	--	4.9/98	--	5.1/102	4.7/94	4.8/96	--	5.0/100	4.9/98	
N44B3	4.8/100	4.2/88	3.8/79	4.1/85	--	--	3.9/81	3.8/79	3.9/81	--	4.0/83	3.9/81	
N64BK5	4.2/100	4.1/98	4.0/95	3.8/91	--	4.0/95	4.0/95	4.2/100	4.1/98	4.0/95	4.0/95		
N65BK5	4.2/100	4.0/95	4.0/95	3.9/93	3.9/93	4.0/95	4.1/98	4.3/102	4.0/95	4.1/98	4.1/98		
N71AK2	4.1/100	3.9/95	3.9/95	3.7/90	3.7/90	3.9/95	--	4.0/98	3.8/93	3.8/93	3.8/93		
N78AK5	4.0/100	4.3/86	4.1/82	4.0/80	4.0/80	4.2/84	4.2/84	4.4/88	4.2/84	4.2/84	4.2/84		
N80AK6	4.3/100	3.9/91	3.9/91	3.6/84	3.6/84	--	3.7/86	4.0/93	3.8/88	3.8/88	3.7/86		
N85BK3	4.2/100	3.9/93	3.9/93	3.7/88	3.8/91	3.9/93	3.8/91	4.1/98	3.9/93	3.9/93	3.8/91		
N86C5	6.6/100	5.4/82	5.3/80	5.5/83	5.5/83	5.5/83	5.6/85	5.7/86	--	5.6/85	5.4/82		
N99AK5	4.8/100	4.5/94	--	4.4/92	--	4.5/94	4.4/92	4.4/92	--	4.4/92	4.3/90		
N99AK6	4.6/100	4.2/91	--	4.3/93	--	4.4/96	4.2/91	4.2/91	--	4.2/91	4.2/91		
N99AK8	4.8/100	4.5/94	--	4.3/90	--	4.5/94	4.4/92	4.4/92	--	4.4/92	4.4/92		
N99AK9	4.5/100	4.4/98	--	4.3/96	--	4.4/98	4.3/96	4.3/96	--	4.3/96	4.3/96		
Ave.	(100)	94	90	90	90	92	92	95	94	92	92	92	96
Standard Deviation		4.7	5.4	5.0	4.9	5.1	5.2	6.2			4.6		

13

Table XI. Actual and Relative AM1 Efficiencies of 1968 Cells on Dry Shelf Storage

Months on Test

Cell No.	0	3	6	9	12	15	18	21	24	27	30	33	36
N127CK3	4.1/100	3.9/95	3.8/93	--	3.8/93	4.1/100	4.0/98	3.9/95	4.1/100	4.0/98	--	4.0/94	4.0/98
N128AK1	4.2/100	3.8/93	3.8/93	--	3.8/93	4.0/95	3.9/93	3.9/93	4.0/95	3.9/93	--	3.9/93	3.9/93
N128AK4	4.3/100	4.1/95	3.9/91	--	--	4.0/93	--	4.1/95	4.4/102	4.2/98	--	4.1/95	4.1/95
N128AK9	3.9/100	3.8/97	3.7/95	--	3.8/97	--	3.8/97	3.8/97	4.0/102	3.8/97	--	3.8/97	3.8/97
N163BK1	4.0/100	4.0/100	3.9/98	4.0/100	--	4.1/103	4.1/103	--	4.0/100	--	4.0/100	--	3.9/98
N163BK5	4.2/100	4.0/95	3.9/93	4.0/95	--	4.2/100	4.1/98	--	4.1/98	--	4.1/98	--	4.0/95
N163BK9	4.0/100	4.0/100	3.8/95	3.9/98	--	4.1/103	3.9/98	--	4.0/100	--	4.0/100	--	3.9/98
N167CK2	4.0/100	3.8/95	3.7/93	3.8/95	--	3.9/98	3.8/95	--	3.8/95	--	3.9/98	--	3.8/95
N185BK3	3.8/100	3.6/95	3.6/95	3.7/97	3.8/100	--	3.7/97	3.9/103	3.7/97	--	3.7/97	3.7/97	
N186AK2	3.8/100	3.6/95	3.6/95	3.7/97	3.7/97	3.8/100	3.8/100	3.8/100	3.9/103	--	3.7/97	3.7/97	
N186BK4	3.8/100	3.6/95	3.6/95	3.7/97	3.8/100	3.7/97	3.8/100	3.9/103	3.8/100	--	3.7/97	3.7/97	
N186BK7	3.9/100	3.6/92	3.6/92	3.7/95	3.8/98	3.8/98	3.8/98	3.9/100	3.9/100	--	3.8/98	3.8/98	
N190BK4	4.3/100	4.2/98	--	4.2/98	4.3/100	4.3/100	4.3/100	4.4/102	4.3/100	--	4.2/98	4.3/100	
N196CK4	4.0/100	3.7/93	--	3.7/93	3.8/95	3.8/95	4.3/107	3.8/95	--	3.8/95	--	3.7/93	
N197AK1	4.0/100	3.7/93	--	3.7/93	3.8/95	3.8/95	3.7/93	3.8/95	--	3.8/95	--	3.8/95	
N202BK9	4.1/100	3.8/93	--	3.9/95	4.1/100	4.0/98	3.9/95	4.0/98	--	3.9/95	--	3.9/95	
N263AK7	3.8/100	3.5/92	--	3.6/95	3.6/95	3.5/92	3.6/95	3.6/95	--	3.6/95	3.6/95		
N263CK8	3.8/100	3.6/95	--	3.7/97	3.7/97	3.7/97	3.8/100	3.7/97	--	3.7/97	3.7/97		
N264BK6	4.0/100	3.6/90	--	3.8/95	3.7/93	3.8/95	3.8/95	3.7/93	--	3.8/95	3.7/93		
N266AK1	4.0/100	3.7/93	--	4.0/100	3.9/98	3.8/95	3.9/98	3.9/98	--	3.9/98	3.8/95		
N279BK4	3.9/100	3.9/100	3.8/98	3.7/95	3.8/98	3.9/100	3.9/100	3.8/98	--	3.8/98	3.8/98		
N280AK1	3.7/100	3.5/95	3.9/105	3.9/105	3.8/103	3.7/100	3.8/103	3.6/97	--	3.7/100	3.6/97		
N280AK3	3.8/100	3.7/97	3.8/100	3.8/100	3.7/97	3.8/100	3.8/100	3.8/100	--	3.8/100	3.7/97		
N280AK8	3.8/100	3.7/97	3.8/100	3.9/103	3.8/100	3.8/100	3.9/103	3.8/100	--	3.8/100	3.8/100		
N289CK6	4.1/100	4.0/98	4.1/100	4.1/100	4.1/100	4.2/103	4.1/100	4.1/100	4.1/100	--	4.1/100		
N290AK3	4.1/100	4.0/98	4.1/100	4.0/98	4.1/100	4.2/102	4.1/100	--	4.1/100	--	4.1/100		
N291BK1	4.1/100	4.0/98	4.1/100	4.0/98	4.1/100	4.1/100	4.1/100	--	4.1/100	--	4.1/100		
N292AK2	4.1/100	3.9/95	4.0/98	3.9/95	4.0/98	4.0/98	4.1/100	--	4.1/100	--	4.0/98		
N300CK6	3.9/100	3.9/100	3.9/100	3.9/100	3.9/100	4.1/103	3.9/100	--	3.9/100	--	3.8/97		
N300CK9	3.9/100	3.9/100	3.9/100	3.8/98	3.8/98	4.0/103	3.9/100	--	3.9/100	--	3.9/100		
N301AK3	3.9/100	4.0/103	3.9/100	--	3.9/100.	4.0/103	4.0/103	--	4.0/103	--	3.9/100		
N301BK5	3.9/100	3.8/98	3.8/98	--	3.8/98	3.9/100	3.7/95	--	3.8/98	--	3.7/95		
N308CK9	3.9/100	3.8/98	4.0/103	--	3.9/100	4.0/103	3.9/100	--	3.7/95	3.8/97			
N309AK1	3.8/100	3.7/97	3.8/100	3.8/100	3.8/100	4.0/105	3.8/100	--	3.8/100	3.8/100			
N313AK4	3.9/100	3.8/98	3.9/100	3.9/100	3.9/100	3.8/98	3.8/98	--	3.8/98	3.8/98			
N314CK8	3.9/100	3.9/100	3.8/98	4.0/103	3.9/100	4.0/103	4.0/103	--	3.9/100	3.9/100			
N326BK8	4.3/100	4.2/98	4.3/100	4.3/100	4.2/98	4.2/98	4.2/98	4.2/98	--	4.2/98			
N326CK5	4.4/100	4.3/98	4.4/100	4.4/100	4.3/98	4.4/100	4.3/98	4.3/98	--	4.3/98			
N327BK7	4.2/100	4.1/98	4.1/98	4.2/100	4.1/98	4.3/102	4.1/98	4.1/98	--	4.1/98			
N327CK3	4.2/100	4.2/100	4.2/100	4.3/102	4.2/100	4.3/102	--	4.3/102	--	4.2/100			
N348AK6	3.9/100	4.0/103	4.0/103	4.0/103	4.2/108	3.9/100	--	3.9/100	--	3.9/100			
N348CK1	4.1/100	4.1/100	4.2/103	4.2/103	4.3/105	4.2/103	--	4.2/103	--	4.1/100			
N349CK2	4.0/100	4.0/100	3.9/98	4.0/100	4.2/105	3.9/98	--	4.0/100	--	4.0/100			
N350BK4	4.1/100	4.1/100	4.1/100	3.4/83	3.5/85	4.0/97	--	4.0/97	--	4.0/97			
Ave.	(100)	97	98	98	98	99	99	98	99	98	98	96	96
Standard Deviation		2.5		3.9			3.6			2.0		2.4	

14

Table XII. Actual and Relative AM0 Efficiencies of 1969 Cells on Dry Shelf Storage

Cell No.						Months on Test							
	0	2	4	6	8	10	12	14	16	18	20	22	24
7-264	3.2/100	3.2/100	3.2/100	3.3/103	3.3/103	--	3.2/100	--	3.2/100	--	--	3.2/100	
7-265	3.2/100	3.2/100	3.2/100	3.1/97	3.2/100	--	3.2/100	--	3.2/100	--	--	3.1/97	
30-546	3.5/100	3.5/100	3.6/103	--	3.5/100	--	--	3.5/100	--	--	3.5/100		
30-862	3.7/100	3.6/97	3.7/100	3.8/103	--	3.7/100	--	--	3.7/100	--	3.6/97		
51-542	3.5/100	3.5/100	--	--	3.5/100	--	3.5/100	--	--	3.5/100			
51-545	3.6/100	3.6/100	--	3.6/100	--	--	3.7/103	--	--	3.6.100			
76-868	3.4/100	3.4/100	--	--	3.4/100	--	3.4/100	--	--	3.3/97			
86-764	3.5/100	3.4/97	--	--	3.4/97	--	3.4/97	--	--	3.3/94			
98-566	3.0/100	3.1/103	--	3.0/100	--	--	3.0/100	--	3.9/97				
98-652	3.2/100	3.2/100	--	3.2/100	--	--	3.1/97	--	3.1/97				
98-654	3.0/100	3.2/107	--	3.1/103	--	--	3.1/103	--	3.1/103				
105-751	3.1/100	3.2/103	--	3.1/100	--	--	3.1/100	--	3.1/100				
132-262	2.8/100	--	2.9/104	--	--	2.9/104	--	--	2.9/104				
135-256	3.0/100	--	3.0/100	--	--	3.0/100	--	--	3.0/100				
Ave.	(100)	101	101	101	100	101	100	100	100	98	98	98	
Standard Deviation		1.8		2.0			1.9		2.6				

15

Table XIII. Actual and Relative AM0 Efficiencies of 1970 Cells on Dry Shelf Storage

Cell No.	Months on Test								
	0	1	2	3	4	5	6	7	8
298-148	3.1/100	3.1/100	3.3/106	3.1/100	3.1/100	3.1/100	3.2/103	3.1/100	3.0/97
299-642	3.5/100	3.4/97	3.7/106	3.6/103	3.5/100	3.5/100	3.5/100	3.5/100	3.4/97
313-346	3.2/100	3.3/103	3.1/97	3.1/97	3.1/97	3.2/100	3.1/97	3.0/94	
315-261	3.3/100	3.5/106	3.4/103	3.3/100	3.3/100	3.3/100	3.3/100	3.2/97	
319-759	3.7/100	3.5/95	3.5/95	3.5/95	3.6/97	3.5/95	3.4/92		
320-346	3.8/100	3.7/97	3.6/95	3.6/95	3.7/97	3.6/95	3.6/95		
341-651	3.5/100	3.4/97	3.5/100	3.4/97	3.3/94				
341-654	3.4/100	3.3/97	3.4/100	3.4/100	3.3/97				
331-746	3.2/100	3.2/100	3.3/103	3.3/103	3.2/100				
331-748	3.3/100	3.3/100	3.4/103	3.3/100	3.2/97				
347-457	3.1/100	3.2/103	3.2/103	3.0/97					
348-654	3.3/100	3.5/106	3.4/103	3.4/103					
352-159	3.1/100	3.0/97	2.9/94						
354-361	3.1/100	3.0/97	2.9/94						
Ave.	(100)	100.	100	99.	98.	98.	98.	98.	97
Standard Deviation		3.5	4.2	1.2	1.9	2.4	3.6		

16
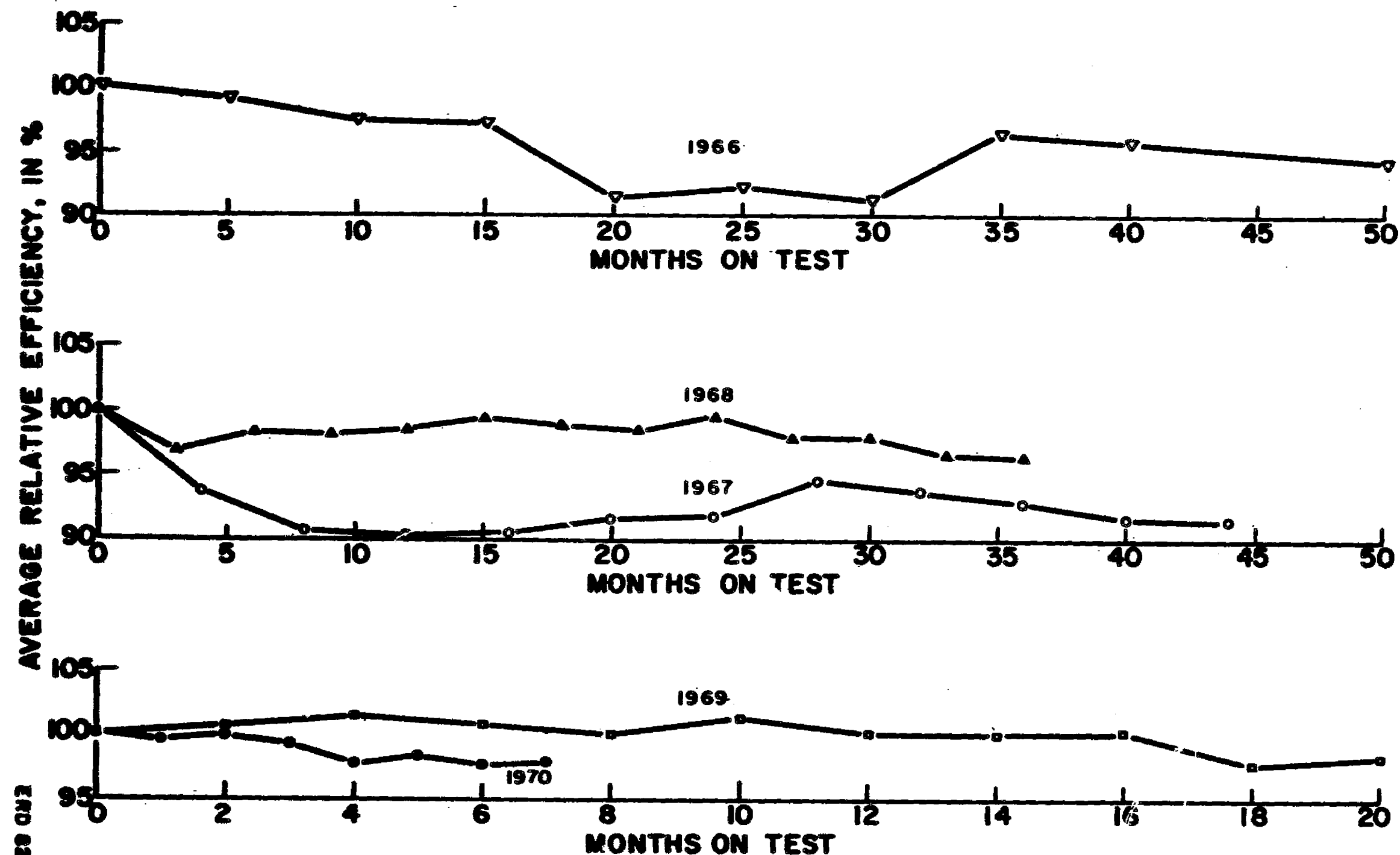
FIG. 1: AVERAGE RELATIVE EFFICIENCIES OF CELLS ON DRY SHELF STORAGE BY YEAR OF MANUFACTURE.
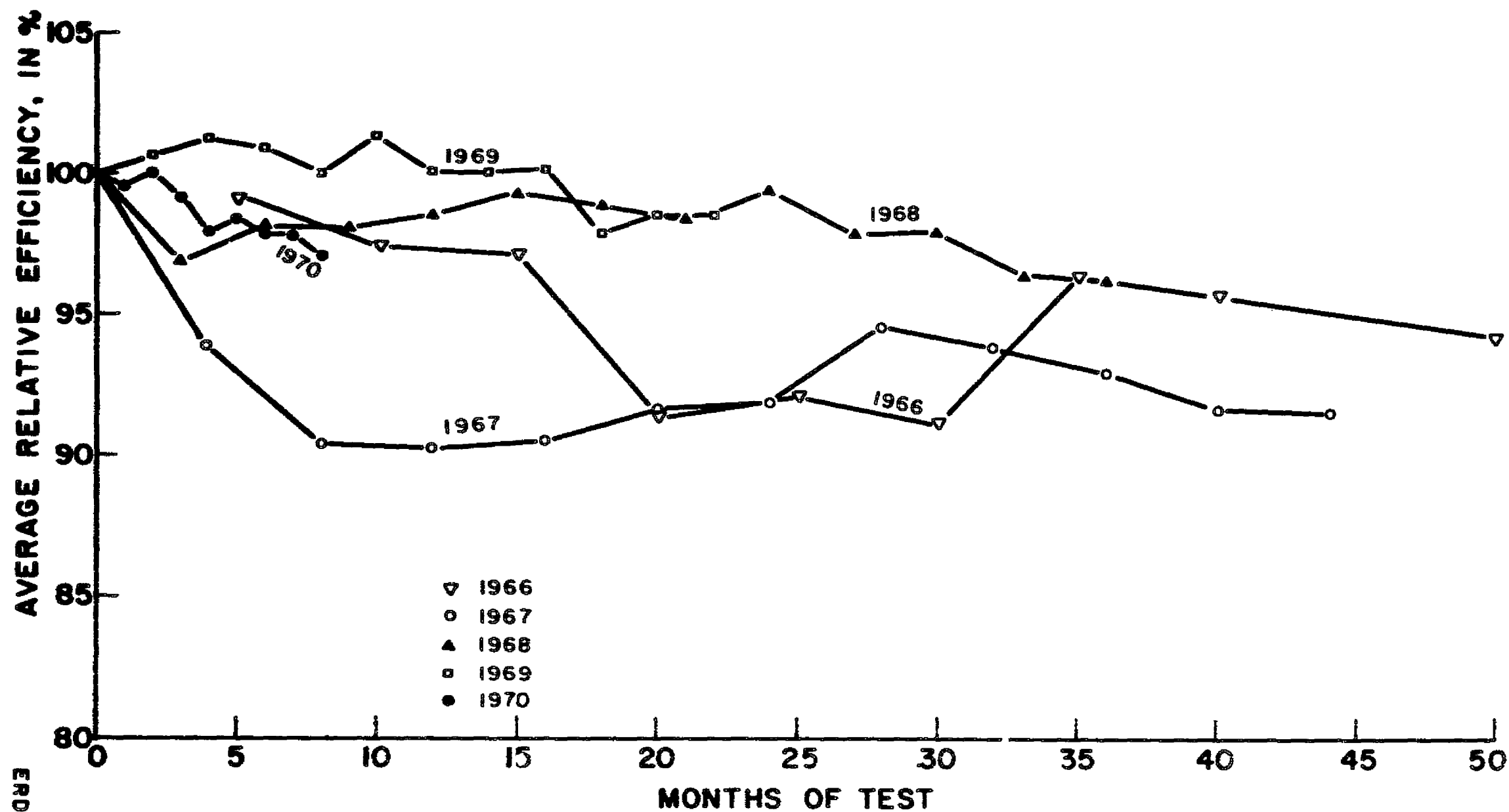
FIG. 2 : AVERAGE RELATIVE EFFICIENCIES OF CELLS ON DRY SHELF STORAGE BY YEAR OF MANUFACTURE.

between the initial value of fill and stability. Also, no correlation was observed between the stability of the fill and stability of the maximum power. In fact, several initially low fill cells increased their fills significantly but still showed a significant decrease in cell output.

Table XIV has been compiled to demonstrate the wide variation present in the data and the difficulty in interpreting the results. The cells are not rigorously typical, since they were selected to demonstrate some extreme behavior, but their performance is representative of the variations present. The first six cells had low fills initially and the change in relative maximum power is seen to vary from a 15% decrease to a 4% increase. The remaining five cells had much higher fills initially but their relative maximum powers changed between a - 10% to a -1%. Hence the initial value of fill was of little benefit in predicting the dry shelf stability of these cells. The only parameter that showed any indication of a correlation with the relative maximum power was the relative SCC, and even here there were glaring exceptions. Cell D521F for example indicated an 8% drop in SCC but this was accompanied by a 1% increase in maximum power. Note however that its fill increased by 9%, which apparently compensated the decrease in SCC. Cell No. N127CK3 which had a 69.7% initial fill showed a fairly stable output while N264BK6, a 70.0% fill cell, showed over a 9% decrease in maximum power.

Table XIV. Performance of Selected Cells on Dry Shelf Storage

| Cell No. | Initial Fill, % | Months on Test | Performance After Storage | | | |
			Relative OCV	Relative SCC	Relative Max. Power	Relative Fill
D296B	62.4	54	100	80	85	106
D315A	61.4	54	100	79	88	110
D364F	57.6	54	102	96	104	108
D403B	63.9	53	100	91	94	104
D522F	59.8	47	100	91	92	100
D521F	56.8	47	101	92	101	109
N31BK4	69.4	45	100	92	90	98i
N86C5	67.5	41	98	82	92	103
N99AK6	68.6	40	97	94	90	98
N127CK3	69.7	37	101	98	99	100
N264BK6	70.0	31	101	92	91	98

19

The initial fill, averaged by year, of all cells entered on to dry shelf storage is shown in Table XV.

Table XV.   Average Initial Fill of all Cells on Dry Shelf Storage

Year	Average Initial Fill
1966	62. 9
1967	65. 7
1968	69. 2
1969	70. 0
1970	69. 1

There appears to be little correlation at least between fill and dry shelf stability. However, as mentioned before, the fabrication process was coming under increasing control during the same time period and the increasing stability by year may simply be reflecting this fact.

High Humidity Storage. - The high humidity storage test, also referred to at times as wet shelf storage and as moisture storage, was incorporated as part of cell testing quite early in the thin film solar cell development program when one of the first cell designs was found to be hygroscopic. These cells failed quite rapidly on exposure to high humidity conditions. Stability on moisture storage has since then become an important performance criterion of all subsequent cell designs. A saturated solution of NH_4Cl, which at room temperature equilibrates with its environment at a relative humidity of approximately 80%, provides the moist atmosphere.

Tables XVI through XX show the actual and relative efficiencies of cells on moisture test by year of manufacture. Also shown are the averages by months on test and standard deviations where deemed significant. Figure 3 shows plots of the average relative efficiency by year of manufacture.

It is apparent from these data that degradation on this test is much more severe than on the dry shelf storage test. Cell failures are quite frequent. Figure 3, which shows plots of the average relative efficiency by year of manufacture of all surviving cells, indicates that two degradation rates appear to be present, a quite rapid initial rate that extends to about 15 months, and a more gradual rate that lasts indefinitely. However, since all cells that failed (efficiencies decreased to below 75% of their initial values) were not included in these averages the second rate is probably much greater than indicated. Table XXI shows the performance parameters of a number of selected cells that failed after the indicated time on test. The initial fills are also listed to show that little correlation between stability and fill is present. Table XXII shows the relative performance parameters of a number of selected cells that survived the test. Comparison of the two groups indicates that loss of SCC is common to both groups, the degree of loss is obviously greater in the cells that failed than in the surviving cells. Loss of fill and OCV are more prevalent

20

Table XVI. Actual and Relative AM1 Efficiences of 1966 Cells on Long Term Humidity Storage

Cell No.	0	5	10	15	20	25	30	35	40	45	50	55	60
					Months on Test								
D187B	6.2/100	5.2/84	5.3/86	5.2/84	5.1/82	5.0/81	5.0/81	4.9/79	4.9/79	4.7/76	5.0/81	4.7/76	4.7/76
D297C	5.1/100	4.2/82	4.3/84	4.2/82	4.0/78	4.0/78	--	3.8/75	3.8/75	3.8/75	3.8/75	3.6/71	Off
D348C	5.4/100	4.4/82	4.6/85	4.4/82	4.1/76	--	4.0/74	4.0/74	4.0/74	4.1/76	4.2/78	3.8/70	Off
D350C	4.3/100	4.5/105	4.2/98	4.2/98	3.7/86	3.7/86	3.6/84	3.5/82	3.3/77	--	3.3/77	3.2/75	Off
D350F	4.7/100	4.0/85	4.2/89	4.3/92	3.8/81	--	3.8/81	3.8/81	4.0/85	4.0/85	4.1/87	4.1/87	
D357E	5.2/100	4.4/85	4.2/81	4.0/77	3.9/75	3.8/73	3.8/73	3.8/73	3.5/67	Off			
D372A	4.5/100	4.2/93	4.0/89	4.0/89	3.6/80	3.7/82	3.7/82	3.7/82	3.6/80	--	3.5/78	3.4/76	
D401B	5.2/100	4.8/82	5.0/96	4.2/81	4.0/77	3.8/73	--	3.4/65	3.6/69	Off			
D405A	4.8/100	4.4/92	4.3/90	4.1/85	--	--	3.9/81	4.0/83	3.8/79	3.7/77	3.6/75		
D411F	4.6/100	4.3/94	4.0/87	3.9/85	--	--	3.7/81	3.8/83	3.8/83	3.6/78	3.6/78		
D424E	5.6/100	512/93	5.0/89	4.7/84	--	4.4/79	4.3/77	4.1/73	4.4/79	4.2/75	4.0/72	Off	
Ave.	(100)	90	88	85	79	79	79	77	77	77	78	76	
Standard Deviation		6.6	4.7	5.5	3.4	4.4	3.6	5.5	5.2	3.2	4.0	5.5	

21

Table XVII. Actual and Relative AM1 Efficiencies of 1967 Cells on Long Term Humidity Storage

Cell No.	Months on Test												
	0	4	8	12	16	20	24	28	32	36	40	44	48
D436E	5.0/100	4.5/90	4.2/84	4.0/80	4.0/80	3.7/74	3.5/70	3.7/74	3.5/70	3.7/74	--	3.7/74	3.5/70
D454A	4.3/100	4.2/86	3.9/80	3.5/72	3.4/70	3.4/70	Off						
D476A	4.9/100	4.6/94	4.1/84	4.3/88	4.2/86	4.1/84	4.0/80	4.1/84	3.9/80	4.1/84	--	4.0/80	4.0/80
D430B	4.9/100	4.4/90	4.1/84	4.0/80	3.9/80	3.7/76	3.6/74	3.6/74	Off				
D485A	4.9/100	4.5/92	4.5/92	4.2/86	4.1/84	4.0/82	4.0/82	4.0/82	3.7/76	3.9/80	--	3.8/78	3.7/76
D487C	5.2/100	4.9/94	4.9/94	4.5/87	4.5/87	4.5/87	4.4/85	4.4/85	4.1/79	4.5/87	--	4.3/83	4.2/81
D506B	5.3/100	4.9/93	4.9/93	4.4/83	--	4.4/83	--	4.3/81	4.1/77	4.1/77	--	4.0/76	3.9/74
D509E	5.1/100	4.4/86	4.4/86	3.8/75	3.7/73	--	3.6/71	Off					
D516D	5.0/100	4.4/88	4.5/90	4.0/80	--	3.8/76	--	3.7/74	3.4/68	Off			
D526C	4.3/100	3.8/88	4.0/93	3.6/84	--	3.3/77	--	3.3/77	3.1/72	3.2/75	3.0/70	Off	
D580E	4.7/100	3.9/83	3.7/79	3.6/77	3.6/77	3.6/77	3.6/77	3.5/75	3.5/75	--	3.5/75	Off	
D585C	5.3/100	4.5/85	4.2/79	3.9/74	3.6/68	Off							
N14B8	4.9/100	4.7/96	4.5/92	4.4/90	4.4/90	4.4/90	4.3/88	4.3/88	4.3/88	--	4.4/90	4.0/82	
N17B3	4.9/100	4.1/84	3.6/74	3.2/65	Off								
D615C	5.3/100	4.8/91	4.4/83	3.8/72	4.1/77	4.1/77	3.9/74	3.8/72	3.7/70	Off			
N38B7	4.4/100	3.9/89	3.6/82	3.2/73	3.1/71	Off							
N51B8	5.2/100	4.8/92	4.2/81	3.7/71	3.9/75	3.7/71	Off						
N52B4	4.8/100	4.6/96	3.7/77	3.3/69	--	3.5/73	Off						
D639C	4.6/100	--	3.7/81	3.4/74	3.4/74	3.3/72	3.3/72	Off					
N72B5	5.4/100	5.3/98	--	5.0/93	4.7/87	4.7/87	4.7/87	4.7/87	--	4.5/83	4.3/80		
NH194CK9	3.9/100	3.4/87	3.1/80	3.2/82	--	3.1/80	3.1/80	2.8/72	2.6/67	Off			
N97BK2	4.9/100	4.1/83	3.9/80	3.7/76	3.7/76	3.7/76	3.7/76	3.5/72	--	3.5/72	3.4/69	Off	
N99BK3	4.9/100	4.2/86	3.9/80	3.8/78	3.9/80	3.9/80	3.7/76	3.7/75	--	3.6/74	3.5/72		
N99BK5	5.0/100	4.3/86	3.9/78	4.0/80	--	4.0/80	4.0/80	3.9/78	3.7/74	3.6/72			
Ave.	(100)	89	84	79	78	79	78	78	75	78	76	79	76
Standard Deviation		4.3	5.7	6.9	7.1	5.4	5.5	5.4	5.7	5.1			

Table XVIII. Actual and Relative AM1 Efficiencies of 1968 Cells on High Humidity Storage

Cell No.	0	3	6	9	12	15	18	21	24	27	30	33	36
						Months on Test							
N115BK8	4.3/100	3.8/88	3.6/84	3.7/86	3.7/86	3.7/86	3.6/84	3.5/81	3.3/77	--	3.1/72	Off	
N116CK5	4.0/100	3.6/90	3.3/83	3.3/83	3.3/83	2.9/73	Off						
N117BK8	4.0/100	3.6/90	3.5/88	3.5/88	3.5/88	3.5/88	3.4/85	3.3/83	3.1/78	--	3.0/75	--	2.9/73
N127BK4	4.1/100	3.8/93	3.7/90	3.7/90	3.7/90	3.5/85	3.3/81	3.2/78	3.1/76	--	2.9/71	Off	
N127BK6	4.2/100	3.8/91	3.7/88	3.7/88	3.7/88	3.7/88	3.5/83	3.4/81	3.1/74	Off			
N127CK1	4.2/100	3.8/91	3.7/88	3.6/86	3.6/86	3.6/86	3.5/83	3.3/79	3.1/74	Off			
N127CK4	4.3/100	4.0/93	3.8/88	3.9/91	4.0/93	3.9/91	4.0/93	3.7/86	3.4/79	--	3.2/74	Off	
N164AK1	4.1/100	3.0/73	3.0/73	Off									
N164BK5	4.0/100	3.6/90	3.5/88	3.5/88	3.4/85	3.5/88	3.2/80	--	3.1/78	--	2.9/73	Off	
N164BK9	3.9/100	3.5/90	3.4/87	3.5/90	3.5/90	3.4/87	3.3/85	3.3/85	3.2/82	--	3.0/77	--	3.0/77
N167CK4	4.0/100	3.7/93	3.5/88	3.6/90	3.6/90	3.8/95	3.3/83	--	3.3/83	--	3.2/80		
N172CK4	4.1/100	3.8/93	3.6/88	3.6/88	3.6/88	3.7/90	3.5/85	3.6/88	3.5/85	--	3.3/80	--	3.2/78
N185CK4	3.8/100	3.4/90	3.3/87	3.4/90	3.4/90	3.3/87	3.3/87	3.2/84	3.0/79	--	2.9/76	Off	
N185CK8	4.0/100	3.6/90	3.5/88	3.6/90	3.5/88	--	3.4/85	3.5/88	3.4/85	--	3.3/83	3.4/85	
N186AK4	4.0/100	3.7/93	3.6/90	3.7/93	3.8/95	3.6/90	3.5/88	3.5/88	3.4/85	--	3.2/80	3.2/80	
N198BK2	3.6/100	3.1/86	3.1/86	3.1/86	3.0/83	2.9/81	3.0/83	2.8/78	--	2.7/75	--	2.6/72	Off
N199AK5	3.8/100	3.7/97	3.8/100	3.7/97	3.8/100	3.6/95	3.6/95	3.4/90	--	3.3/87	--	3.2/84	
N199AK7	3.8/100	3.7/97	3.8/100	3.7/97	3.8/100	3.6/95	--	3.5/92	--	3.3/87	--	3.2/84	
N199BK4	3.9/100	3.8/97	3.9/100	3.9/100	3.9/100	3.7/95	3.7/95	3.6/92	--	3.5/90	--	3.3/85	
N265BK4	3.9/100	3.6/92	3.6/92	--	3.4/87	3.4/87	3.4/87	3.3/85	--	3.1/80	3.0/77		
N265BK5	4.0/100	3.8/95	3.7/93	3.8/95	3.7/93	3.6/90	3.5/88	3.6/90	--	3.3/83	3.3/83		
N265BK7	3.8/100	3.6/95	3.6/95	3.6/95	3.6/95	3.4/90	3.5/92	3.5/92	--	3.2/84	3.1/82		
N265CK6	4.0/100	3.7/93	3.8/95	3.7/93	3.8/95	3.5/88	3.5/88	3.5/88	--	3.2/80	3.2/80		
N278AK4	3.9/100	3.7/95	3.7/95	3.5/90	3.5/90	3.5/90	3.3/85	--	3.2/82	--	3.1/80		
N280AK2	3.8/100	3.7/97	3.7/97	3.8/100	3.6/95	3.6/95	3.4/90	--	3.3/87	--	3.2/82		
N280AK4	3.7/100	3.5/95	3.5/95	3.5/95	3.4/92	3.4/92	3.2/87	--	3.1/84	--	3.0/81		
N280AK9	3.9/100	3.6/92	3.8/97	3.6/92	3.6/92	3.6/92	3.3/85	--	3.3/85	--	3.2/82		
N290AK2	4.2/100	4.0/95	3.9/93	--	3.8/91	3.8/91	3.5/83	--	3.5/83	--	3.4/81		
N290BK3	4.2/100	4.0/95	4.0/95	--	3.8/91	3.8/91	3.7/88	--	3.6/86	--	3.6/86		
N290BK6	4.2/100	3.9/93	3.8/91	--	3.7/88	3.7/88	3.4/81	--	3.3/79	--	3.2/76		
N292AK5	4.2/100	3.9/93	3.9/93	3.9/93	3.8/91	3.8/91	3.5/83	--	3.4/81	--	3.4/81		
N301AK1	4.0/100	3.8/95	3.8/95	--	3.3/83	3.4/85	3.3/83	--	3.0/75	3.0/75			
N301AK4	4.0/100	3.9/98	3.8/95	--	3.6/90	3.7/93	3.5/88	--	3.3/83	3.1/78			
N301AK9	4.0/100	3.7/93	3.8/95	--	3.6/90	3.6/90	3.6/90	--	3.4/85	3.3/83			
N301CK5	3.9/100	3.6/92	3.7/95	--	3.4/87	3.6/92	3.5/90	--	3.2/82	3.1/80			
N313BK4	4.0/100	3.6/90	3.7/93	--	3.3/83	3.3/83	3.2/80	--	2.9/73	Off			
N313CK8	4.0/100	3.6/90	3.6/90	--	3.2/80	3.1/78	3.0/75	Off					
N313CK9	4.0/100	3.7/93	3.7/93	3.5/88	3.4/85	3.5/88	2.7/68	Off					
N314CK1	4.0/100	3.6/90	3.5/88	3.5/88	3.3/83	3.3/83	3.3/83	--	3.1/78	2.9/73			
N324AK4	4.3/100	4.1/95	4.1/95	3.9/91	4.0/93	3.8/89	--	3.5/82	--	3.5/82			
N324BK4	43/100	4.1/95	4.0/93	3.7/86	3.7/86	3.6/84	--	3.4/79	--	3.4/79			
N329BK7	4.3/100	4.0/93	3.7/86	3.6/84	3.5/82	3.3/77	--	3.1/72	Off				
N329BK9	4.2/100	4.0/95	3.9/93	3.7/88	3.8/91	3.4/81	--	3.4/81	--	3.3/79			
N348AK5	4.1/100	3.9/95	3.8/93	3.6/88	--	3.5/85	--	3.2/78	--	3.1/76	Off		
N349AK2	4.2/100	3.9/93	3.8/91	3.6/86	3.6/86	3.5/83	--	3.2/76	--	3.1/74	Off		
N353AK6	4.2/100	4.0/95	3.9/93	3.6/86	--	3.5/83	--	3.2/76	--	3.1/74	Off		
N356CK7	4.0/100	3.6/90	3.3/83	3.0/75	Off								
Ave.	(100)	92	91	90	89	88	85	83	84	81	80	82	76
Standard Deviation		3.9		4.6		4.9			4.0		3.8		

Table XIX. Actual and Relative AM0 Efficiencies of 1969 Cells on High Humidity Storage

Cell No.	0	2	4	6	8	10	12	14	16	18	20	22	24
N400AK3	3.6/100	3.5/97	--	3.4/95	3.4/95	3.2/89	--	--	--	--	--	--	
20-362	3.3/100	3.2/97	--	3.1/94	3.1/94	3.0/91	--	--	2.7/85	--	--	2.7/85	
30-542	3.6/100	3.4/95	--	3.3/92	3.2/89	3.0/83	--	--	2.9/81	--	--	2.8/78	
32-861	3.2/100	3.2/100	--	3.1/97	3.1/97	3.0/93	--	--	2.9/91	--	2.8/88		
40-665	3.7/100	3.5/95	--	3.5/95	3.4/92	--	3.2/87	--	--	3.2/87			
44-346	3.9/100	3.6/92	--	3.5/90	3.4/87	--	3.3/85	--	--	3.2/82			
76-861	3.5/100	3.3/94	--	3.3/94	3.2/92	--	3.1/89	--	--	3.1/89			
76-866	3.6/100	3.4/94	--	3.4/94	3.3/92	--	3.1/86	--	--	3.1/86			
98-658	3.3/100	3.4/103	3.0/91	2.9/88	--	--	2.7/82	--	2.7/82				
98-659	3.3/100	3.2/97	3.2/97	3.0/91	--	--	2.9/88	--	2.8/88				
105-652	3.2/100	3.1/97	3.0/94	2.8/88	--	--	2.8/88	--	2.7/84				
105-654	3.2/100	2.9/91	2.8/88	2.6/81	--	--	2.6/81	--	2.5/78				
134-762	2.9/100	--	2.8/97	2.7/93	--	--	2.7/93	--	2.6/90				
134-765	2.9/100	--	2.8/97	2.7/93	--	--	2.8/97	--	2.6/90				
Ave.	(100)	96	94	92	92	89	88		85	86			
Standard Deviation		3.2	3.5	3.9	3.0	3.7	4.5		4.3	2.6			

24

| | | | | | Months on Test | | | | | |
Cell No.	0	1	2	3	4	5	6	7	8	9
300-145	3.7/100	3.4/92	3.6/97	3.3/89	3.2/87	3.2/87	3.3/89	3.1/84	3.0/81	
300-748	3.4/100	3.2/94	3.4/100	3.0/88	3.0/88	3.0/88	3.0/88	2.9/85	2.8/82	
315-358	2.9/100	2.8/97	2.4/83	2.4/83	2.3/79	2.3/79	2.2/76	2.2/76		
308-768	3.6/100	3.6/100	3.3/92	3.3/92	3.2/89	3.3/92	3.3/92	3.2/89		
319-153	3.5/100	3.2/91	3.0/86	3.1/89	3.0/86	2.9/83	2.9/83			
324-859	3.0/100	2.6/87	2.5/83	2.5/83	2.5/83	2.4/80	2.4/80			
327-143	2.9/100	2.8/97	2.8/97	2.6/90	2.5/86					
331-745	3.0/100	3.0/100	3.0/100	2.9/97	2.8/93					
333-464	3.0/100	2.7/90	2.6/87	2.4/80	2.3/77					
333-469	3.0/100	2.8/93	2.7/90	2.5/83	2.5/83					
346-747	3.3/100	3.2/97	3.1/94	3.0/91						
347-168	2.9/100	2.8/97	2.7/93	2.6/90						
352-155	3.2/100	2.9/91	2.9/91							
369-746	4.0/100	3.6/90	3.5/88							
Ave.	(100)	94.	91.	88.	85.	85.	84.	83.	81	
Standard Deviation		3.9	5.5	9.9	4.5	5.2	5.0			

Table XXI. Performance of Selected Cells that Failed on High Humidity Storage

Cell No.	Initial Fill	Months on Test	Performance After Storage			
			Relative OCV	Relative SCC	Rel. Max. Power & Eff.	Relative Fill
N164AK1	72. 1	32	95	76	63	88
N116CK5	70. 5	36	91	67	55	91
N313CK9	69. 2	24	97	82	74	94
D401B	69. 1	41	96	81	63	82
N17B3	69. 0	33	90	66	48	84
D357E	67. 0	43	96	76	70	98
N51B8	67. 0	32	94	72	63	95
D585C	66. 1	33	87	53	38	86
N52B4	66. 0	32	100	72	66	93
D639C	65. 8	30	96	71	63	97
N97BK2	65. 0	36	95	74	68	96
D509E	64. 6	35	94	62	54	98
D480B	64. 1	36	96	73	71	102
D454A	64. 0	36	96	68	64	103
D516D	62. 8	35	97	74	70	100
N38B7	59. 3	32	93	71	58	88
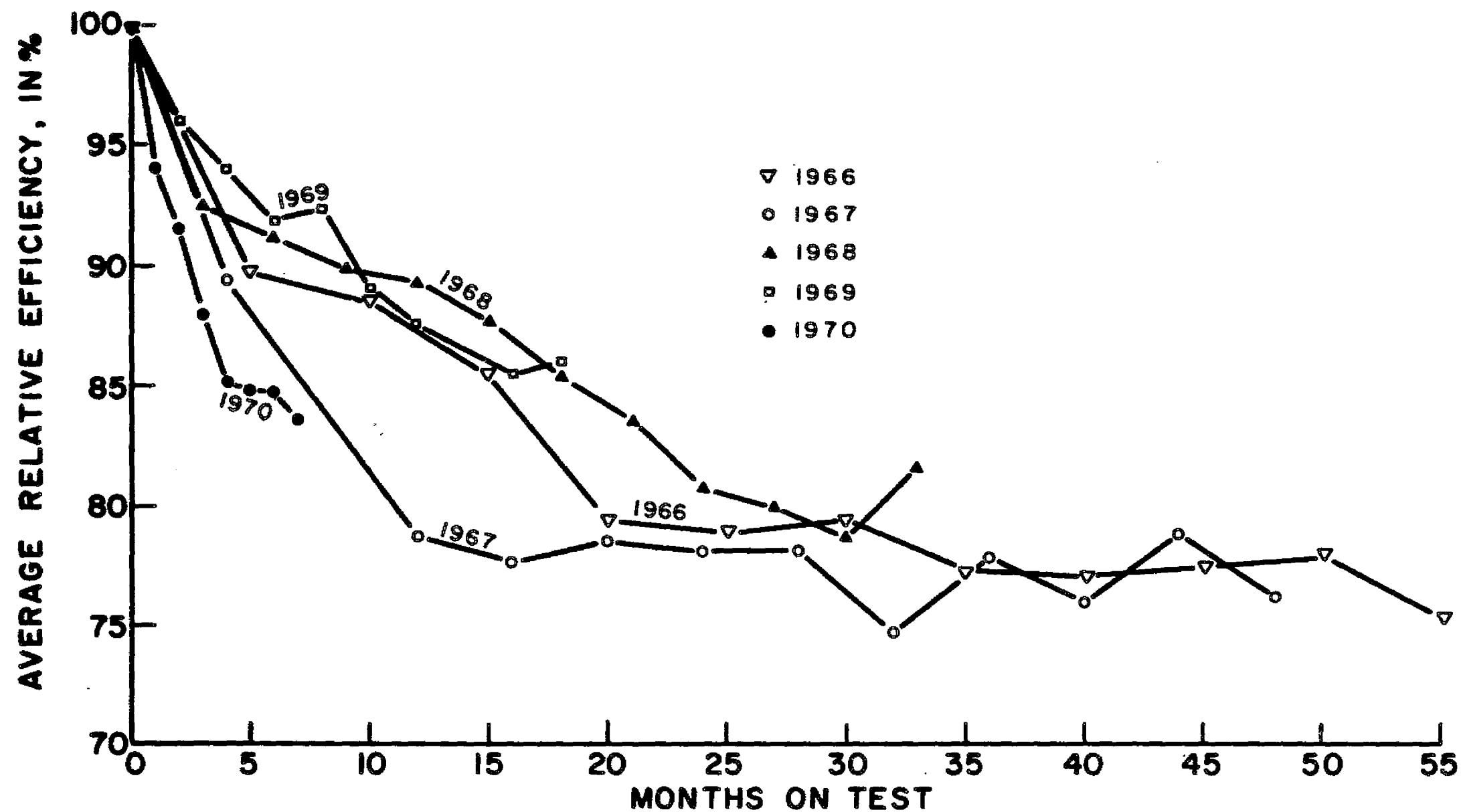
FIG. 3: AVERAGE RELATIVE EFFICIENCY OF CELLS ON HIGH HUMIDITY STORAGE BY YEAR OF MANUFACTURE.

Table XXII.   Performance of Selected Cells That Did Not Fail
in High Humidity Storage

Cell No.	Cover	Initial Fill	Months on Test	Performance After Storage			
				Relative OCV	Relative SCC	Relative Max. Power	Relative Fill
D350F	M	55.0	56	100	74	87	116
D411F	M	62.6	52	98	78	78	102
D487C	M	63.4	48	99	78	80	104
D476A	M	61.7	48	99	86	86	100
N14B8	M	64.0	45	98	84	82	99
N72B5	M	65.5	41	99	79	80	100
N185CK8	K	71.2	34	100	80	76	95
20362	K	68.1	22	97	84	81	97
32851	K	69.4	21	99	85	86	101
76861	K	70.6	18	100	86	87	101
134765	K	69.1	16	100	89	90	100

in the cells that failed than in the surviving cells, however, several of the cells that failed showed no loss in fill, e.g., D480B, D454A, and D516D. The loss in OCV appears to be greater among the cell failures than among the cells that survived, but, there are exceptions, e.g., N52B4. It appears that there are at least two independent degradation mechanisms present: one which affects the SCC appears to be present in all cells, while the other which affects the fill is quite inconsistent in its appearance.

It is tempting to relate loss of OCV with loss of fill, and indeed, among the surviving cells no significant decreases are present in either parameter. Among the failures however inconsistencies are present. If variations exceeding 5% are considered significant, then loss of fill did occur when loss of OCV did not, e.g., N52B4, D401B and N164AK1. But loss of OCV always occurred with a loss of fill, the exceptions are only marginal, e.g., D509E.

The degradation seen on both the dry and wet shelf storage appears to be quite similar, differing only in degree. In fact, the relative parameters of the cells that survived moisture testing, such as those listed in Table XII, resemble quite closely the parameters of cells that degraded most on dry shelf storage, shown in Table XXIII. These two groups show practically no decrease in fill, only a decrease in SCC which appears to be the cause of the decrease in maximum power and efficiency. Since the cells that failed on moisture test, such as those listed in Table XXI, showed decreases in fills in addition to large decreases in SCC, it is tempting to conclude that some constituent in the moist atmosphere triggers the fill degradation mechanism in addition to aggravating the SCC degradation mechanism. No cell has failed or even shown a significant reduction in performance on these two tests without a corresponding significant decrease in SCC. However, many cells have failed without showing a significant decrease in fill, e.g., N480B, D454A and D516D. So the same constituent that was suspected of causing the adjustment process in recent production cells may also be responsible for the degradation observed on moisture storage.

Table XXIII.   Parameters of Cells that Degraded Most on Dry Shelf Storage

				Performance After Storage			
Cell No.	Cover	Initial Fill	Months on Test	Relative OCV	Relative SCC	Relative Max. Power	Relative Fill
D296B	M	62.4	54	100	80	85	106
D306D	M	66.0	54	100	80	85	107
D289D	M	65.3	54	99	80	86	108
D292D	M	64.5	54	100	80	85	107
N44B3	M	6..3	44	98	92	82	92
N78AK5	K	65.2	41	99	85	83	100
N86C5	M	67.5	41	98	82	83	103

The response of degraded cells to recovery attempts affords some insight into the nature of the degradation. A number of the cells that had failed on moisture storage were subjected to the same lamination cycle and vacuum bake that is used during the fabrication process to attach the grid and the cover plastic. This has been done frequently in the past with varying degrees of success in restoring degraded cells and in improving the performance of other poor cells.

Table XXIV shows the effect of storage in room atmosphere for 1 month and for 10 months on cells that had failed on moisture storage. The initial parameters are listed, followed by the relative parameters after removal from moisture storage, and then the relative parameters after either the 1 or 10 month room atmosphere storage. It is apparent that there is no tendency for these cells to recover by themselves.

Table XXV shows the effects of subjecting degraded cells to either the relamination cycle and 16 hour 135°C vacuum bake or the 16 hour vacuum bake by itself. The first four cells were given only the vacuum bake, the next six were given both the relamination cycle and the 16 hour bake. The effects of the vacuum bake alone are varied, D526C was essentially unchanged, N127CK1 decreased while N164BK5 and N313BK4 improved their performance. Five months later the improved cells had suffered some decrease while the other two had remained the same.

Of more significance was the effect of both the relamination cycle and the vacuum bake on the six remaining cells. In all cases the SCC and maximum powers showed substantial improvements while the fills increased in four cells and decreased in two. The two cells that were tested five months later showed that the effects were not permanent however, both had substantial decreases in their parameters but had not decreased to their degraded levels prior to relamination.

If some constituent of the moist atmosphere had been responsible for the initial degradation, perhaps by adsorption on the barrier layer after penetrating the cover plastic, the 16 hour 135°C vacuum bake would be expected to drive off the offender and partially restore at least the initial performance. However since a relamination cycle, in addition to the bake, was required before significant restoration occurred some other mechanism is implied. The lamination cycle referred to consists of a 20 minute exposure at 185°C and at a pressure of 100 psi, and it is quite possible that the short interval at the higher temperature does the same thing that the vacuum bake does, only much faster. It is equally probable however, that the lamination cycle was re-establishing the initial grid contact which had become loose as a result of moisture storage. It is obvious that a complete definition of the mechanism of moisture degradation will not be obtained from these data.

Table XXIV   Effect of Storage in Room Atmosphere on Moisture Degraded Cells

Cell No. (Months on Test)	Initial Parameters	Relative Parameters After Moisture Storage	1 Month Storage in Room Atmosphere	10 Month Storage in Room Atmosphere
N349AK2 (26 months)				
OCV	.469 V	98	97	
SCC	.709 A	76	78	
Pmax	.230 W	73	73	
Fill	69.2 %	99	98	
N127CK4 (36 months)				
OCV	.474 V	99	97	
SCC	.704 A	80	76	
Pmax	.236 W	73	70	
Fill	72.0 %	92	93	
N198BK2 (34 months)				
OCV	.450 V	97	96	
SCC	.651 A	77	79	
Pmax	.199 W	71	71	
Fill	67.9 %	97	94	
N185CK4 (34 months)				
OCV	.479 V	98	98	
SCC	.629 A	80	79	
Pmax	.206 W	73	73	
Fill	68.3 %	94	95	
N52B4 (32 months)				
OCV	.452 V	100		98
SCC	.890 A	72		68
Pmax	.265 W	64		52
Fill	66.0 %	93		78
N17B8 (33 months)				
OCV	.476 V	90		88
SCC	.820 A	66		60
Pmax	.270 W	48		43
Fill	69.0 %	84		82
D357E (43 months)				
OCV	.495 V	96		96
SCC	.860 A	76		72
Pmax	.265 W	70		66
Fill	67.0 %	98		96
D401B (41 months)				
OCV	.465 V	96		93
SCC.	.885 A	81		80
Pmax	.285 W	63	53	
Fill	69.1 %	82		72
D509E (35 months)				
OCV	.479 V	94		96
SCC	.900 A	62		64
Pmax	.278 W	54	63	
Fill	64.0 %	98		102

Table XXV. Effect of Subsequent Heat Treatment on Degraded Cells

Cell No. (Months on Test)	Initial Parameters	Relative Parameter After Moisture Storage	16 Hr., 135°C Vacuum Bake	Relamination and 16 Hr. Vacuum Bake	5 Month Room Air Storage
D526C (44 months)					
OCV	.482 V	97	96		95
SCC	.765 A	73	78		74
Pmax	.236 W	72	70		68
Fill	64.0 %	102	94		97
N127CK1 (33 months)					
OCV	.478 V	96	92		90
SCC	.643 A	81	78		78
Pmax	.234 W	63	47		44
Fill	76.1 %	81	65		62
N164BK5 (32 months)					
OCV	.439 V	96	98		96
SCC	.741 A	74	83		78
Pmax	.221 W	70	83		75
Fill	68.0 %	98	102		99
N313BK4 (25 months)					
OCV	.451 V	97	98		98
SCC	.689 A	79	89		84
Pmax	.220 W	71	80		76
Fill	70.7 %	94	92		93
D462E (46 months)					
OCV	.460 V	98		98	
SCC	1.024 A	88		102	
Pmax	.318 W	63		87	
Fill	67.5 %	73		87	
N127BK2 (32 months)					
OCV	.460 V	101		98	
SCC	.743 A	83		110	
Pmax	.239 W	50		72	
Fill	68.9 %	60		68	
D580E (42 months)					
OCV	.467 V	96		100	97
SCC	.860 A	78		92	87
Pmax	.256 W	72		93	79
Fill	63.6. %	96		101	93
N254AK8 (26 months)					
OCV	.457 V	96		98	96'
SCC	.752 A	65		89	84
Pmax	.232 W	63		88	76
Fill	70.0 %	98		96	91
N313CK8 (25 months)					
OCV	. . . V	96		97	
SCC	.770 A	76		103	
Pmax	.220 W	67		94	
Fill	68.3 %	92		94	
N356CK7 (23 months)					
OCV	.470 V	96		97	
SCC	.690 A	76		96	
Pmax	.224 W	69		85	
Fill	68.9 %	95		92	

100°C Vacuum Storage. - The 100°C vacuum stability test was initiated in 1966 to accelerate any temperature dependent degradation mechanisms that may be present in the cell. This test is more severe than either the dry or wet shelf storage tests and even borders on being destructive since operation of solar cell arrays under these conditions is only a remote possibility. The test results are quite varied and fluctuate over a wide range which probably reflects the severity of the test, and makes their interpretation difficult. As mentioned earlier the test was interrupted for 3 months in 1968 for a complete overhaul of the system, hence all cells on test prior to that time were additionally subjected to a three month desiccated storage at room temperature. No significant effects were attributed to this interruption and it is assumed that cell performance after the test resumed was the same as prior to the suspension.

The test facility itself is a heated vacuum oven maintained at a pressure of 10^{-5} Torr by an oil diffusion pump and an LN_2 trap. In order to prevent atmospheric exposure of test cells while at temperature, great care was always taken to make certain that the system had cooled down to room temperature before breaking vacuum to allow entry of new cells and testing of existing cells.

The actual and relative efficiencies of all cells on this test are listed by year in Tables XXVI through XXIX. Cells from both 1966 and 1967 are listed in Table XXVI. None of the 1966 cells and only one of the 1967 cells has survived, where survival is defined as maintaining greater than 75% of initial output. Tables XXVI and XXVII appear to indicate that not too many cells survive beyond a 28 to 30 month barrier, i.e., more cells appear to fail in this time interval than any other. However, there are many exceptions, e.g., 1967 cell, H107B8, has survived for 40 months and 1968 cell, N165BK9, which after 33 months is still remarkably close to its initial performance level. These exceptions indicate that the 28 to 30 month barrier is not intrinsic to the cell but is related to some fabrication parameter that is not constant. If any intrinsic degradation mechanism exists on this test its effects up to 33 months at least are negligible.

There appear to be two separate degradation mechanisms also present on this test, one that affects the SCC and another that affects the fill. In contrast to the dry and wet shelf degradation, degradation of fill appears to be of more significance on this test than SCC degradation, because a number of cells that failed showed no degradation in SCC but all showed degradation of fill. Just the opposite conditions occurred in cells that failed on wet shelf storage, i.e., SCC degradation was present in all cells but degradation of fill was not. Table XXX has been compiled from cells that were selected from 100°C vacuum failures to show the two types of degradation. It should be observed that fill degradation is common to all cells but SCC degradation is not. In fact cells H107B8 and N290AK5 even showed a significant increase in SCC which somewhat compensated for large decreases in their fills and prevented their classification as failures, although only narrowly.

The decrease in fill again appears attributable to an increase in series resistance. An increasing series resistance has been observed previously on this test[1] and was thus associated with an increase in the resistance of the

Table XXVI. Relative and Actual Efficiencies of 1966 and 1967 Cells on 100°C Vacuum Storage

Cell No.	Months on Test

Cell No.	0	4	8	12	16	20	24	28	32	36	40	44
D379E	5.1/100	5.1/100	4.7/92	4.0/79	3.0/59	Off						
D368F	4.8/100	4.9/102	4.2/88	3.9/81	3.6/75	3.3/69	Off					
D392A	5.1/100	5.1/100	4.5/88	4.1/81	3.6/71	Off						
D401F	4.5/100	4.8/107	4.0/89	4.0/89	3.6/80	3.6/80	--	2.3/51	Off			
D407D	4.9/100	--	3.7/76	3.3/67	Off							
D412F	4.1/100	4.3/105	4.1/100	3.9/95	3.8/93	--	3.6/88	3.3/81	3.1/76	2.5/61	Off	
D438D	5.6/100	5.7/106	4.5/81	4.3/77	3.3/59	Off						
D462E	6.1/100	5.7/94	5.2/85	5.1/84	4.8/79	--	4.7/77	4.5/74	4.4/72	Off		
D504E	5.5/100	5.3/96	4.6/84	4.0/73	3.9/71	Off						
D514E	4.9/100	4.5/92	4.3/88	3.4/69	Off						Pyre ML over spray	
D554E	5.2/100	4.3/94	4.6/89	4.1/79	3.5/67	Off						
D579E	4.6/100	4.4/96	4.3/93	4.1/89	4.0/87	1.7/37	Off					
D586B	5.0/100	4.8/96	4.5/90	4.6/92	4.5/90	4.9/98	4.9/98	4.3/86	4.5/90	2.3/46	Off	
H107B8	5.0/100	5.3/106	4.8/96	4.5/90	5.0/100	4.9/98	4.7/94	4.9/98	4.7/94	--	3.8/76	
H108A4	5.0/100	5.3/106	4.7/94	4.4/88	--	4.4/88	4.1/83	4.2/84	--	2.5/50	Off	
H108B5	5.1/100	5.3/104	5.0/98	4.7/92	--	4.7/92	4.3/84	4.4/86	3.9/77	--	2.9/57	Off
N74B8	5.1/100	4.2/82	3.9/76	3.4/67	Off							
N85BK7	4.5/100	4.1/91	3.8/84	3.4/76	3.2/71	Off						
N98BK4	4.9/100	4.6/94	3.5/78	--	2.5/51	Off						
N98BK5	5.0/100	4.6/92	3.8/76	--	2.0/40	Off						
N99BK4	4.7/100	4.5/96	3.4/72	--	1.5/32	Off						
Ave.	(100)	98	86	82	70	80	87	80	82			
Standard Deviation		6.4	7.4	8.7								

Table XXVII. Actual and Relative Efficiencies of 1968 Cells on 100°C Vacuum Storage

Cell No.	Months on Test											
	0	3	6	9	12	15	18	21	24	27	30	33
N111AK2	4.0/100	3.6/90	2.4/60	Off								
N112AK5	4.2/100	4.2/100	4.0/95	4.0/95	4.1/98	4.0/95	4.1/98	3.9/93	--	4.0/95	--	3.9/93
N113CK8	4.2/100	4.1/98	3.7/88	3.8/91	3.8/91	3.7/88	3.6/86	3.4/81	--	3.5/83	--	3.3/79
N116AK8	4.5/100	4.4/98	4.3/96	4.5/100	4.4/98	4.4/98	4.4/98	4.3/96	--	4.4/98	--	4.1/91
N127BK2	4.4/100	4.2/96	4.0/91	4.0/91	4.0/91	3.3/75	3.4/77	3.3/75	--	2.7/61	Off	
N127BK8	4.4/100	4.3/98	4.3/98	4.4/100	4.5/102	4.4/100	4.5/102	4.3/98	--	4.2/96	--	3.4/77
N128BK5	4.8/100	4.5/94	4.0/83	3.8/79	3.5/73	2.9/60	Off					
N128BK6	4.4/100	4.1/93	3.8/86	3.8/86	3.9/89	3.6/82	3.6/82	3.5/80	--	3.5/80	--	3.2/73	Off
N163BK3	4.0/100	3.8/95	3.4/85	3.3/83	3.0/75	2.7/70	Off					
N163BK6	4.1/100	4.1/100	3.9/95	3.9/95	--	3.4/83	3.4/83	3.2/78	--	3.0/73	Off	
N164AK2	4.2/100	4.1/98	4.0/95	4.1/98	--	4.0/95	4.1/98	4.0/95	--	4.0/95	--	4.0/95
N165BK9	4.2/100	4.2/100	4.1/98	4.1/98	4.3/102	--	4.3/102	4.0/95	--	4.2/100	--	4.3/103
N171BK4	4.0/100	3.7/92	3.5/88	3.4/85	2.8/70	Off						
N185BK4	4.0/100	3.7/92	3.4/85	3.2/80	--	2.4/60	Off					
N186CK5	3.9/100	3.7/95	3.7/95	--	3.4/87	3.0/77	3.3/85	3.1/80	--	3.1/80	2.5/64	Off
N187AK5	4.2/100	4.0/95	3.9/98	4.0/95	3.2/76	2.9/69	Off					
N199BK5	4.4/100	4.3/98	4.3/98	4.2/95	3.9/89	3.9/89	3.8/86	--	3.5/80	--	3.2/73	Off
N200CK9	3.7/100	3.5/95	3.5/95	3.5/95	3.6/97	3.6/97	3.3/89	--	3.5/95	--	3.5/95	
N199AK4	4.1/100	4.0/98	3.9/95	4.0/98	3.9/95	4.0/98	3.8/93	--	3.8/93	--	3.7/90	
N202BK6	4.1/100	4.0/98	4.0/98	4.0/98	3.9/95	4.0/98	3.8/93	--	3.9/95	--	3.7/90	
N262BK5	4.0/100	4.0/100	3.9/98	--	3.4/85	3.4/85	3.2/80	--	3.0/75	--	2.4/60	Off
N262BK7	4.0/100	4.0/100	4.0/100	--	3.6/90	3.7/93	3.5/88	--	3.5/88	--	3.1/77	
N264BK7	3.9/100	3.8/98	3.8/98	--	3.4/87	3.5/90	3.3/85	--	3.1/79	--	2.9/74	Off
N265BK1	4.0/100	4.1/103	4.0/100	--	3.8/95	3.9/97	3.7/93	--	3.7/93	--	3.6/90	
N278AK1	3.9/100	3.8/98	3.8/98	--	3.7/95	3.9/100	3.8/98	--	3.8/100	--	2.8/72	Off
N278AK5	3.8/100	3.8/100	3.8/100	--	3.6/95	3.7/97	3.6/95	--	3.6/95	--	3.3/87	
N278AK7	3.9/100	3.7/95	3.7/95	--	3.7/95	--	3.8/98	--	4.0/103	--	3.2/82	
N279BK5	3.9/100	3.5/90	2.9/74	--	Off							
N290AK5	4.3/100	4.3/100	4.4/102	--	4.1/95	4.2/98	4.1/95	--	4.1/95			
N290BK1	4.2/100	4.1/98	4.1/98	--	3.9/93	3.8/90	3.6/86	--	3.6/86	--	3.2/76	
N290BK4	4.3/100	4.4/102	4.3/100	--	3.9/91	3.9/91	3.6/83	--	3.4/79	--	2.8/65	Off
N290BK7	4.3/100	4.3/100	4.3/100	--	4.0/93	4.0/93	3.9/91	--	3.8/88	--	3.5/81	
N300CK2	4.0/100	3.9/98	3.9/98	--	3.4/85	3.5/88	3.5/88	--	3.2/80	3.0/75		
N301AK8	4.0/100	3.9/98	3.9/98	--	3.7/93	3.8/95	3.6/90	--	3.8/95	3.6/90		
N301CK2	4.1/100	4.2/102	4.1/100	--	4.1/100	4.2/102	4.0/98	--	3.9/95	3.7/90		
N301CK7	4.1/100	4.0/98	4.0/98	--	3.8/93	4.0/98	3.8/93	--	3.9/95	3.9/95		
N309BK5	3.8/100	4.1/108	--	3.8/100	3.7/98	3.8/100	3.7/98	--	3.4/90	3.0/79		
N313BK7	4.1/100	4.1/100	4.2/102	--	4.0/98	4.1/100	4.0/98	--	4.0/98	3.8/93		
N314CK5	4.0/100	4.1/103	4.1/103	--	4.0/100	4.0/100	3.8/95	--	3.8/95	3.6/90		
N314CK8	4.1/100	4.1/100	4.1/100	--	4.0/98	4.2/102	3.9/95	--	3.8/93	3.7/90		
N324BK5	4.3/100	4.4/102	--	3.8/89	4.0/93	3.7/86	--	3.5/81	--	3.2/75		
N324CK4	4.3/100	4.4/102	--	4.2/98	4.2/98	3.9/91	--	3.9/91	--	3.7/86		
N329BK4	4.4/100	4.4/100	--	4.0/91	4.1/93	3.8/86	--	3.5/80	--	3.2/73	Off	
N330BK7	4.5/100	4.6/102	--	4.1/91	4.2/93	3.9/87	--	3.8/85	--	3.5/78		
N348BK5	4.1/100	4.3/105	--	3.9/95	4.1/100	3.7/90	--	3.7/90	--	3.5/86		
N348CK4	4.2/100	4.3/102	--	3.9/93	4.1/98	3.9/93	--	3.7/87	--	3.6/86		
N350AK2	4.1/100	4.1/100	--	3.7/90	3.8/93	3.6/88	--	3.3/81	--	3.0/73	Off	
N353AK5	4.4/100	4.4/100	--	3.6/82	3.9/89	3.7/84	--	2.6/55	Off			
Avg.	(100)	99	95	93	93	90	91	84	91	85	76	86
Standard Deviation		2.8				9.4				9.7		

34

Table XXVIII. Actual and Relative AM0 Efficiencies of 1969 Cells on 100°C Vacuum Storage

Cell No.	Months on Test												
	0	2	4	6	8	10	12	14	16	18	20	22	24
52-68	3.2/100	--	3.4/106	3.2/100	--	3.1/98	3.1/98	--	--	3.1/98	--	3.0/94	
19-861	3.7/100	--	3.8/103	3.8/103	--	3.7/100	3.8/103	--	--	3.7/100	--	3.6/97	
N388C5	3.5/100	--	3.5/100	3.6/103	3.6/103	3.7/106	--	--	3.6/103*	--	--	3.5/100*	
28-655	3.9/100	3.7/95	4.0/103	--	3.6/92	--	--	3.4/87	--	3.2/82			
39-762	3.9/100	3.9/100	4.0/103	4.0/103	3.7/95	--	--	3.5/90	--	3.3/85			
40-664	3.6/100	3.6/100	3.8/105	3.8/105	3.6/100	--	--	3.5/97	--	3.3/92			
27-548	3.3/100	3.4/103	3.5/106	3.5/106	3.3/100	--	--	3.2/97	--	3.0/91			
39-764	3.6/100	3.8/105	3.9/108	3.6/100	3.7/103	--	--	3.5/97	--	3.3/92			
98-656	3.3/100	3.7/112	3.6/109	3.4/103	3.4/103	--	3.4/103	--	3.3/100				
98-655	3.1/100	3.5/113	3.5/113	3.4/110	3.4/110	--	3.5/113	--	2.6/84				
105-655	2.9/100	3.3/114	3.4/117	3.1/107	--	--	3.2/110	--	3.0/103				
107-261	2.9/100	3.2/110	3.0/104	3.0/104	--	--	2.9/100	--	2.9/100				
132-144	2.9/100	--	3.0/104	3.0/104	--	2.9/100	--	--	2.7/93				
132-145	2.8/100	--	3.0/107	--	--	2.9/104	--	--	2.8/100				
Ave.	(100)	106	106	104	101	100	104	94	97	91			
Standard Deviation		2.5	8.8	2.7	4.9								

*Extrapolated from AM1 measurements.

Table XXIX. Actual and Relative AM0 Efficiencies of 1970 Cells on 100°C Vacuum Storate

Cell No.	Months on Test									
	0	1	2	3	4	5	6	7	8	9
301-643	3.6/100	3.7/103	3.7/103	3.6/100	3.5/97	3.6/100	3.7/103	3.6/100	3.6/100	
302-468	3.0/100	3.1/103	3.4/113	3.2/106	3.2/106	3.2/106	3.2/106	3.2/106	3.1/103	
307-444	3.1/100	3.3/106	2.9/94	2.9/94	2.9/94	3.0/97	2.9/94	2.9/94		
316-141	3.5/100	3.7/106	3.4/97	3.4/97	3.3/94	3.6/103	3.5/100	3.5/100		
322-458	3.4/100	1.9/56	Off							
323-543	3.1/100	2.8/90	2.8/90	2.8/90	3.0/97	2.9/93	2.8/90			
341-869	3.4/100	3.4/100	3.4/100	3.4/100	3.3/97					
341-864	3.2/100	3.2/100	3.1/97	2.9/94	2.8/90					
351-565	3.4/100	3.5/103	3.4/100	3.3/97						
352-857	3.3/100	3.5/106	3.4/103	3.4/103						
356-251	3.6/100	3.6/100	3.6/100							
376-455	3.1/100	2.9/93	2.7/87							
Ave.	(100)	101	98.	98.	96.	100.	99.	100		
Standard Deviation		2.6	7.3	4.4	5.1	4.5	5.8			

36

Table XXX.   Selected Cells from 100°C Vacuum Storage Test

Cell No.	Initial Fill	Months on Test	Performance After Storage			
			Relative OCV	Relative SCC	Relative Max. Power	Relative Fill
D412F	61.9	39	98	95	70	69
D401F	66.1	43	95	51	28	58
D462E	67.5	44	98	88	68	83
D586B	67.5	41	90	67	35	59
H107B8	66.1	40	97	113	76	69
H108B5	67.1	39	97	99	57	60
D576E	66.4	31	92	78	39	55
N85BK7	67.1	27	100	99	63	64
N98BK5	68.7	25	100	62	31	50
N111AK2	67.4	22	91	100	54	60
N199BK5	68.6	30	100	97	73	75
N290AK5	68.6	29	99	109	76	70
N329BK4	68.9	27	100	95	73	76
N164AK2	71.7	32	101	109	93	85
N165BK9	70.7	32	103	107	103	94
N301CK7	70.5	28	101	103	95	91
52-68	70.3	22	100	104	92	89
107-261	71.0	16	101	107	98	91

copper compensated CdS layer that lies just below the barrier layer. It was hypothesized earlier[2] that copper diffusion, which is initiated during the heat treatment that follows the barrier formation process, continues at the 100°C maintained on this test and results in an increasing series resistance of the cell. If true, this continued diffusion obviously represents an intrinsic failure mechanism of the thin film cell, but as indicated before, its rate appears to be slow enough that, by itself, it should not limit the useful life of cells. The wide variation in cell life is difficult to reconcile with a common failure mechanism and, if such a failure mechanism does exist, it must do so in addition to the other vagaries already present in the barrier layer fabrication process.

The previously mentioned increase in substrate resistance could also account for the suspected increase in series resistance. Since the proposed alloying mechanism of silver and zinc is also temperature dependent, its subsequent increase in substrate resistance makes it an equally likely candidate for being the responsible failure mechanism. Both of these mechanisms, however, by the nature of their processes, are irreversible; hence recovery is not expected in the performance of cells degraded by either of these mechanisms. Table XXXI shows the results of attempts at recovering the performance of cells that failed on the 100°C vacuum test. The first two cells, D462E and N127BK2, show that heat degraded cells can be at least partially recovered by subjecting them to the lamination cycle and a 16 hour 135°C vacuum bake. The next two cells were only given the vacuum bake and conflicting results were obtained. Cell N74B8 showed no recovery, while D579E showed a very substantial improvement in performance. The next 5 cells were selected to demonstrate the variations in response that were obtained from a group of failures that had been stored in room atmosphere for 10 months. It can be concluded, however, that some recovery in cell performance is possible but nothing resembling complete recovery was approached, which implies that both reversible as well as irreversible degradation effects were present.

It is tempting to associate the reversible effects with the SCC degradation mechanism and the irreversible effects with the fill mechanism because initial SCC could be completely restored and even exceeded in some instances, while the fill could be only partially resotred. Partial recovery of the fill implies the existence of both an irreversible and reversible component in the fill degradation mechanism, which obviously allows the existence of either or both of the previously discussed possible causes of increased series resistance.

Figure 4 shows the I-V characteristics of the four small area cells obtained by cutting a degraded cell into four quarters. The intent was to determine if the degradation was confined to a small area of the cell or if it were spread uniformly over the entire area of the cell. The similarity of the four curves indicates that the entire cell degraded fairly uniformly.

Table XXXI.   Cell Parameters After Recovery Attempts

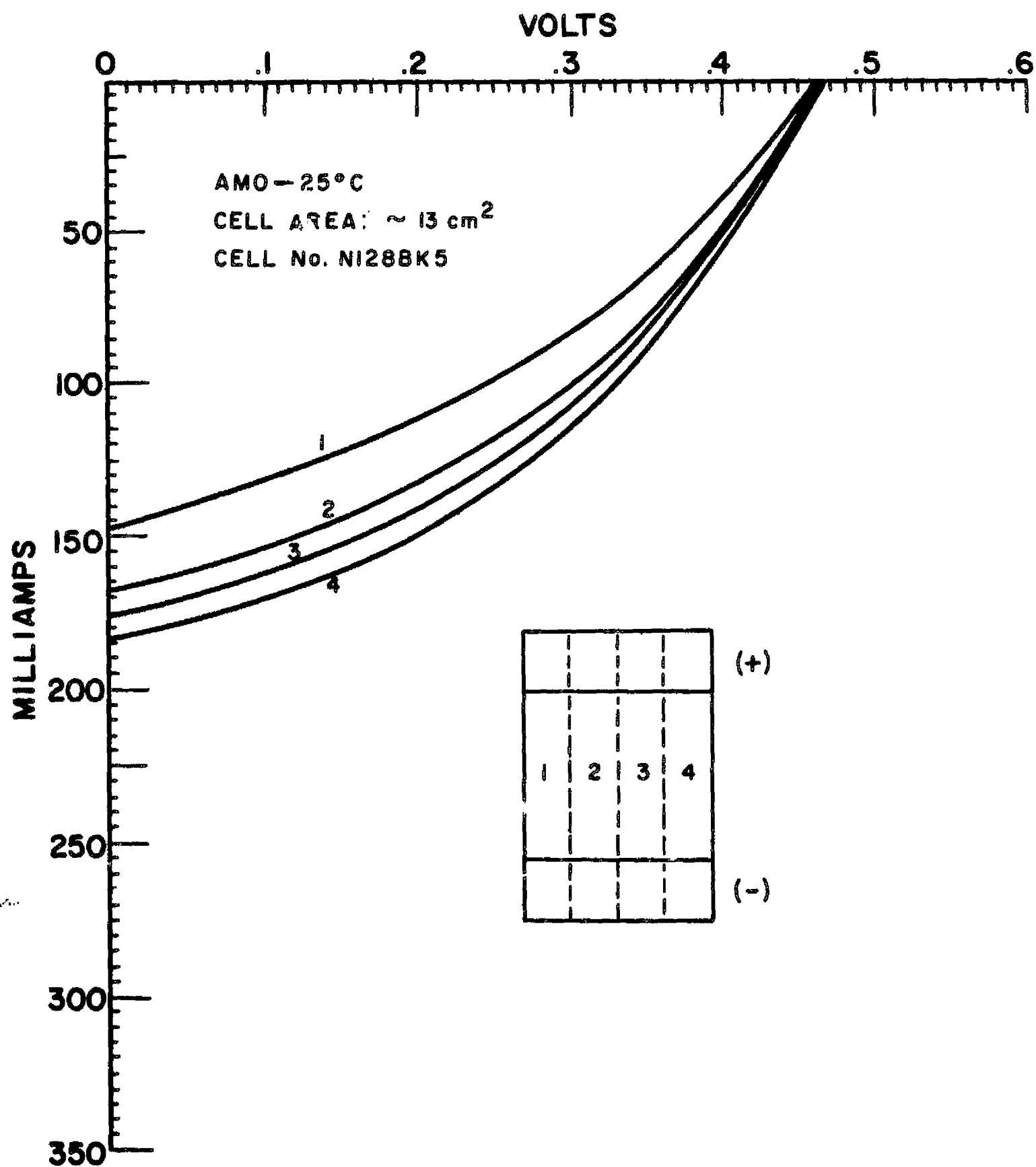| Cell No. (Months on Test)	Initial Parameters	Relative Parameter After 100°C Vacuum Test	16 Hr., 135°C Vacuum Bake	Relamination and 16 Hr., 135°C Vacuum Bake	10 Months Storage in Room Atmosphere
D462E (45 months)					
OCV	.460 V	98		98	
SCC	1.024 A	88		102	
Pmax	.318 W	63		87	
Fill	67.5 %	73		87	
N127BK2 (30 months)					
OCV	.460 V	101		98	
SCC	.743 A	83		110	
Pmax	.239 W	50		72	
Fill	68.9 %	60		65	
N74B8 (25 months)					
OCV	.480 V	95	95		
SCC	.928 A	91	90		
Pmax	.280 W	56	57		
Fill	62.7 %	65	68		
D579E (31 months)					
OCV	.470 V	92	100		
SCC	.808 A	79	97		
Pmax	.252 W	39	81		
Fill	66.4 %	55	83		
D388F (42 months)					
OCV	.470 V	95			101
SCC	.910 A	79			60
Pmax	.260 W	41			35
Fill	60.7 %	55			58
D392 A (43 months)					
OCV	.475 V	93			101
SCC	.915 A	33			65
Pmax	.278 W	20			33
Fill	64.2 %	65			51
N187AK5 (20 months)					
OCV	.470 V	102			101
SCC	.712 A	96			91
Pmax	.233 W	67			61
Fill	69.5 %	69			66
D554 E (30 months)					
OCV	.465 V	101			100
SCC	.992 A	66			47
Pmax	.281 W	37			37
Fill	60.9 %	56			78
D407 D (21 months)					
OCV	.480 V	93			100
SCC	.850 A	49			75
Pmax	.270 W	23			39
Fill	66.3 %	49			52

FIG. 4: I-V CURVES OF FOUR QUARTER CELLS.

40

X-ray diffraction analysis of the substrate of cell D392A, which had been on test for over three years, indicated that the alloying of Ag and Zn was quite advanced. As will be discussed later, the reaction appeared to have reached the point that of the 3 (or possibly 4) known Ag-Zn phases, only the phases of high Ag content were detected. Free zinc and the highest zinc content phase were not detected, implying that an increased substrate resistance was partially responsible for the apparent increase in series resistance.

SUBSTRATE TEMPERATURE CONTROL DURING CdS EVAPORATION

The temperature of the silver-Pyre ML* substrate during CdS evaporation has been the subject of many studies during this as well as previous years' programs. It has been shown[1] that there is a discrepancy between the indicated temperature and the nominal control temperature and that temperature is not uniform over the entire surface of the substrate, rather large gradients having been detected. However, the significance of the discrepancies and gradients has never been understood; their elimination was attempted in the present program by the substitution of two alternate methods of substrate temperature control. In addition, their effects on cell performance were also studied in a set of related studies. A radically different design CdS evaporation source was also evaluated as part of the same task.

Programmed Substrate Temperature Control. - The existing method of controlling substrate temperature during CdS evaporation which has been in use since the production fabrication of thin film cells begun a number of years ago relies on thermocouple control of radiation heating of the unsilvered side of the Kapton film by two tantalum strip heaters. The main heater is approximately the same size as the 11-1/2" x 12" substrate while the second heater, a single strip of tantalum that runs around the periphery of the main heater, was initially installed to heat the edges of the substrate when it was found that the main heater was not adequately doing so. Both heaters are located in the same plane, about a half-inch above the substrate, and the thermocouples which are in pressure contact with the substrate on the side exposed to the heaters provide the existing temperature control.

During the early studies it was determined that, contrary to the original design concept, the small peripheral heater was apparently doing the bulk of the substrate heating and appeared to be the main cause of the temperature gradient observed between the center and edge of the substrate. This was revealed by time-lapse records which showed that power was applied to the small peripheral heater far more frequently than the main heater. Adjustments in the control temperatures of the two heaters were ineffective in alleviating the problem. It was suspected that the temperature control thermocouples were partly responsible for the problem because they made questionable thermal contact with the substrate. The substitution of an alternate temperature control system which avoided the use of thermocouples was investigated. Accordingly a programmed substrate temperature controller was fabricated which allowed power to one substrate station to be applied separately to the

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41

two heaters by a predetermined sequence. The best sequence for each heater was determined empirically and much effort was expended in the experimental determination of these programs. It was found that a typical sequence consisted of three separate phases: the first and the simplest was the initial heat-up phase which obviously consisted of constant power application to both heaters until the substrate temperature approached the nominal 220°C required during the remainder of the cycle. The second phase consisted of establishing and maintaining the substrate at the control temperature, and the third phase began with the application of power to the evaporation sources, initiating the CdS deposition process. Substrate heating by radiation from the sources was significant and required a change in the program of power application to the substrate heaters. The program for this third phase was the most difficult to obtain. A 10°C to 15°C temperature gradient between the center and edge of the substrate during the third phase of substrate heating was typically achieved with the best program obtained. This was a significant improvement over the 45°C gradients seen with the existing thermocouple control systems.

Two substrates whose temperatures during actual CdS evaporation were controlled by the programmed heater were fabricated into completed cells. Table XXXII shows the average AM0-25°C parameters of the resulting cells. Also shown are the averages from the control cells, i.e., from cells whose CdS films evaporated at the same time but whose substrate temperatures were controlled in the usual manner.

Table XXXII. AM0-25°C Performance of Cells With Program Heated Substrates During CdS Evaporation. Averaged According to Substrate

Substrate Number	OCV V	SCC A	Eff. %	Fill %	No. of Cells
362-43	.471	.770	3.1	65.6	6
362-23*	.463	.809	3.3	67.1	9
362-21	.463	.906	3.5	67.1	7
362-53	.469	.808	3.2	65.3	9
362-62*	.459	.784	3.1	66.9	8
362-71	.459	.875	3.5	67.0	7

*Program heated substrates.

While no obvious advantage to programmed substrate heating is apparent in the data, no disadvantages are apparent either. These results are in agreement with those to be discussed shortly from experiments in which CdS films were evaporated onto a wide range of substrate temperatures. In general it appears that the CdS film evaporation process is not critically dependent on substrate temperature, at least as far as the resulting thin film cell performance is concerned.

Conductively Heated Substrates. - The concept of conductively heating substrates during CdS evaporation has always been attractive since many of the problems associated with the present radiantly heated method would be avoided. Elimination of the previously mentioned temperature gradients is one obvious advantage and greater accuracy in substrate temperature determination is another. A substrate holder was designed and fabricated which consisted of a curved 1/4 inch thick aluminum plate. The Kapton substrate was held in tension against the aluminum plate by spring loading two ends. The holder itself was radiantly heated by the previously described substrate heater to the nominal 220°C, the substrate was then conductively heated by thermal contact to the aluminum plate.

The whole concept of heating the substrate in this manner was obviously dependent on the integrity of the thermal contact between the substrate and the aluminum plate. And this contact in turn was dependent on the tension with which the substrate could be held against the plate. The main drawback of the design of the holder was that tension could be applied to the substrate in one direction only. The inability to apply tension in the other direction proved to be the principal deterrent in obtaining a uniform thermal contact.

The temperature distribution on substrates used in these experiments was determined by attaching small thermocouples to the silvered side of standard Kapton substrates with a thermally conductive epoxy. The first attempts at determining the usefulness of the conductively heated substrate concept indicated that the thermal contact was inadequate. Although the aluminum plate came to the required 220°C in very short order, as determined by thermocouples embedded at various points on its surface, the thermocouples on the front surface of the substrate indicated a temperature no greater than 145°C even after over an hour of heating. All attempts to improve the thermal contact did not result in any higher temperatures. Because tension was applied in one direction only a number of longitudinal crinkles were present in the substrate that defied all removal attempts. In addition, there was a natural tendency for the substrate to be pulled away from the plate at those points where the thermocouples were attached.

A simple calculation to determine the equilibrium temperature that the substrate would reach if it is only radiatively heated by the aluminum plate shows maximum temperature of only 77°C. This value is obtained assuming an emissivity of 0.? for the aluminum plate and 0.8 for the Kapton film. Apparently, heat conduction along the silver layer from adjacent areas that are in good thermal contact with the aluminum plate raised the temperature of the film to the observed values.

It appears that the required uniform thermal contact could not be obtained with this particular design of substrate holder, which was selected because of its ease of adaptability to the existing substrate heaters. A design which assures the necessary uniform thermal contact would require a major retooling of the substrate heaters, and in all probability, additional retooling of other components in the evaporator as well. The concept of conductively heated substrates during CdS evaporation cannot be adequately evaluated until this uniform thermal contact can be assured.

CdS Evaporation at Various Substrate Temperatures. - Since significant temperature gradients have been shown to exist across the substrate during CdS evaporation, and since the accuracy of the indicated substrate temperature was somewhat questionable, a study in which the effect of evaporating CdS films on substrates whose temperatures were varied over a wide range was undertaken. In addition to fabricating cells from these experimental films, it was also intended to gather Hall and resistivity data in order to correlate these film parameters with cell performance.

CdS films were evaporated at substrate temperatures that ranged from 180° C to 300° C in 20° C intervals. Five CdS evaporations were made at each substrate temperature in a small experimental evaporator that accommodated a 6-cell substrate. One cell position was masked off during three of the five evaporations to provide the Hall-resistance samples. Visually there was no difference among the films evaporated at the various temperatures except at 280° C and 300° C, where the high substrate temperatures resulted in such thin films that the silver-zinc substrate was readily apparent through the film. All the films were fabricated into cells according to the standard process except the high temperature substrate films which were too thin to withstand the five-second HCl etch prior to barrier formation. The dip time in the etch was reduced as much as possible, to approximately one second, for these high temperature films, but in spite of this preferential treatment none yielded a single normal cell. All cells fabricated from films evaporated at 280° C and 300° C were shorted, indicating that the reduced etch was still too severe.

It was realized that the reduction in film thickness could be partially avoided if the substrate were made the coldest surface in the evaporator during CdS evaporation. Accordingly, one 300° C evaporation was attempted in which an aluminum foil cylinder enclosed the evaporation sources and the substrate. Radiation heating by the evaporation sources was assumed to have heated the foil to at least a higher temperature than that of the bell jar. The bell jar was also lined with aluminum foil to reduce the cooling of the foil cylinder. The resulting CdS films were indeed thicker than the previous films evaporated at 300° C, about 0.4 mils instead of 0.2 mils, but contamination was also present because some areas of the films were blackened. Their resistivities were significantly lower than that of the other 300° C films.

Difficulties were experienced when Hall measurements were attempted on the film samples evaporated at the various temperatures. The one-mil sample thickness resulted in fairly high resistances across the Hall probes which made them highly susceptible to the pick-up of extraneous and spurious voltages. Attempts at shielding, including operation in screened rooms, the use of electrometer input amplifiers, etc. were only partially successful. Reduction of the noise level to below the signal level occurred only on one or two of the low temperature samples, and the results of the few good measurements obtained were relatively meaningless by themselves.

Resistance measurements were taken on all the Hall samples and resistivity data were accumulated at all substrate temperatures. The measurements were taken on film samples evaporated on glass microscope slides. Two slides were positioned on a 3" x 3" tantulum evaporation mask during the deposition process. The glass slides were heated in the same manner as the remainder of the substrate, but since they were of completely different materials and configurations, there is no assurance that their temperatures were the same as the substrates. The results, averaged by substrate temperature, are shown in Table XXXIII. These measurements were all taken in normal room light.

Table XXXIII. Resistivity of CdS Films Evaporated at Different Substrate Temperatures

Substrate Temperature	Average Thickness	ρ, Ohm-cm			No. of Samples
		Min.	Ave.	Max.	
	mils				
180° C	1.2	15	41	111	4
200° C	1. .	44	70	89	6
220° C	.71	26	254	620	6
240° C	.61	15	106	216	4
260° C	.50	344	1650	5900	6
280° C	.29	1330	2010	4400	6
300° C	.20	300	1620	2800	4

The data are characterized by rather large and erratic fluctuations, not only from specimens evaporated at different temperatures but from those evaporated at the same substrate temperature as well. However, such variations have been consistently observed in the resistance measurements that are routinely taken on the CdS films used in cell fabrication, which are evaporated at a nominal substrate temperature of 220° C, so their occurrence here was more or less anticipated. In spite of the fluctuation, a trend of increasing resistance with increasing substrate temperature is apparent. It is not clear though what significance this has as far as cell performance is concerned. No correlation has ever been shown to exist between cell performance and CdS film resistance; in fact, the standard process specifications are quite broad, resistivities between 5 and 100 ohm-cm being acceptable.

The AM0-25° C performance of the cells fabricated from the CdS films evaporated at these various substrate temperatures are averaged in Table XXXIV. The 280° C and 300° C substrate temperature cells as mentioned did not result in functional cells. A fall-off in performance is apparent at both the high and low temperature ends with a rather broad maximum in between. The fall-off at the high temperature end may be due to the increased resistivity, or it may just as well be due to the decreased film thickness. As a basis of comparison for the 180° C substrate cells, the averages of the parameters of cells from

8 standard process substrates that went through barrier formation just before and just after the 180°C substrates, were compiled; the average parameters of 57 cells were: OCV of 0.469 volts, SCC of .878 A, efficiency of 3.6% and fill 66.7%. These values indicate that the SCC and Efficiency of the 180°C substrate cells were indeed significantly lower than standard process cells fabricated at the same time. Similar comparisons for the cells resulting from films evaporated at the other temperatures are not available because all of the substrates evaporated at the same temperature were not barriered together, but on two or even three widely separated days. In general, it does appear that cell performance is not critically dependent on substrate temperature during CdS evaporation, because variations as much as 20°C in either direction apparently have no significant effect.

Table XXXIV. Average Performance of Cells Evaporated at Different Substrate Temperatures

	180°C	200°C	220°C	240°C	260°C	
No. of Cells	21	19	20	20	16	
OCV	.466	.477	.479	.476	.474	V
SCC	.740	.812	.817	.842	.822	A
Eff.	2.9	3.4	3.5	3.5	3.3	%
Fill	65.0	67.6	68.6	63.7	64.6	%

Of interest also are the highest performance cells from each substrate temperature group shown in Table XXXV. These cells were somewhat arbitrarily selected from among the highest fill and highest output power cells within each group. Only the 180°C cell is significantly different from the rest, which again implies that substrate temperature during CdS evaporation is not highly critical.

Table XXXV. Highest Performance Cells From Each Substrate Temperature Group

Cell No.	°C	OCV mV	SCC mA	Pmax mW	Eff. %	Fill %
368-2V5	180	478	788	255	3.33	67.8
371-5V6	200	486	872	285	3.71	71.3
379-1V2	220	479	840	282	3.68	70.1
382-8V2	240	481	875	291	3.78	68.9
389-1V5	260	470	885	283	3.70	68.1

46

Evaluation of Experimental Evaporation Sources. - A variation on the standard process evaporation source was evaluated by evaporating CdS films and fabricating them into completed cells. The sources were furnished by NASA-Lewis based on a design worked out at T.R.W.[8] and differed from the standard process source primarily in the design of the orifice. The orifice in the experimental source was determined by the hole size in two perforated quartz plates located at the top of the cylindrically shaped source. A wad of quartz wool was located between the two plates. The orifice in the standard process source is provided simply by necking down the opening.

The CdS films that resulted from the use of the new sources were practically identical to standard process films. The only obvious difference was a slight decrease in overall film thickness. The 17 gram charge in a standard source usually produces a film thickness of about 1.4 mils, while the same charge in the experimental source resulted in film thicknesses of about 1.0 mil. The difference is thought to be due to the difference in evaporation angles of the two sources. The experimental film resistivity was determined to be 13 ohm-cm which is well within the range normally experienced with standard process films.

Table XXXVI lists the AM0-25°C performance parameters of the eleven Kapton covered cells fabricated from these films. Also listed are six cells fabricated from films evaporated in the same evaporation but using standard process sources.

Table XXXVI.   AM0-25°C Performance of Kapton Covered Cells Fabricated from Experimentally Grown CdS Films

Cell No.	OCV	SCC	P_{max}	Fill	Eff.
320-51	Short				
320-52	Short				
320-53	.471	.740	.244	70.0	3.19
320-54	.471	.750	.243	68.6	3.17
320-56	.469	.743	.240	68.8	3.12
320-71	.462	.782	.239	66.0	3.12
320-72	.466	.788	.252	68.6	3.28
320-73	.462	.810	.238	63.6	3.10
320-74	.450	.740	.163	49.0	2.13
320-75	.462	.808	.243	65.1	3.17
320-76	.459	.775	.212	59.9	2.77
Control Cells					
320-61	.440	.819	.156	43.3	2.0
320-62	.459	.880	.271	67.2	3.5
320-63	.461	.860	.257	65.0	3.3
320-64	.467	.860	.276	68.8	3.6
320-65	.467	.860	.274	69.5	3.6
320-66	.469	.861	.271	67.2	3.5

It was concluded that there was no significant difference between the cells fabricated from these experimental CdS films and standard process films.

47

The experimental evaporation sources were found to be significantly easier to load with CdS powder than the standard sources because of their much wider openings. This was the major difference found between the two types of sources.

SUBSTRATE STUDIES

An evaluation of NASA-supplied silver coated Kapton substrates was undertaken. Thin films of silver had been deposited by a proprietary process onto 3 x 3 inch squares of 1 mil Kapton film. The thickness of the silver layer was measured to be somewhat thinner than the usual Ag-Pyre ML layer. The thickness was less than 0.1 mil on all samples. The resistivity reflected this thinness, being considerably higher than normally experienced with sprayed substrates. The actual values ranged between 0.03 and 0.1 ohms per square. In the standard process 0.015 ohms per square is the upper inspection limit. The polished appearance of the silver layers more resembled silver foil than the matte surface of sprayed Ag-Pyre ML. Light transmission through the proprietary substrates was somewhat greater than normally occurs with sprayed substrates.

The adherence of the silver layer to the Kapton film was found to be considerably poorer than that of sprayed silver-Pyre ML layers. This became particularly evident during processing into cells. Great difficulty was experienced during zinc plating in trying to obtain a uniform layer. Reducing the plating current to the smallest reliable values allowed in the plating bath still resulted in a very poor plate. Spalling, peeling and blistering occurred freely. Only one of the four samples attempted had an area uniformly large enough to warrant further processing.

Five films were used as substrates for CdS evaporation, two as received (detergent scrub only), two were burnished and the last was the best of the zinc plated samples. Because of their odd size, evaporation masks for 2 x 2 cm cells had to be used during CdS evaporation. The adherence of the CdS to the silver was better than of the silver to the Kapton and resulted in some flaking and spalling off of the CdS and silver. Large enough areas were still present on each sample to accommodate a 2 x 2 cm grid, so each was given the standard barrier dip. Surprisingly, this step was least harmful and most samples probed normally during barrier inspection.

A wide range of performances resulted from the gridded cells. Figure 5 shows the I-V characteristic of the best of the resulting cells. Most surprising is that this sample received no zinc plate so the CdS is in direct contact with the silver layer. The only cell from the zinc plated specimen showed a more poorer performance, and all the other cells were also quite poor. But the fact that somewhat normal behavior was obtained from a cell without a zinc interlayer is most interesting. Previous attempts at fabricating cells without interlayers usually resulted in much poorer performing cells, marked by low OCV's and poor fills. It may be that the proprietary method of silver deposition used here performs the same function that zinc plating a sprayed silver-Pyre ML substrate does. It has always been assumed that this function has been to provide an ohmic contact between the CdS and the silver substrate, although last year's work on chrome interlayers indicated that the CdS-silver junction is fabrication, as well as materials, sensitive. However, it is probably premature to form conclusions based on these results.
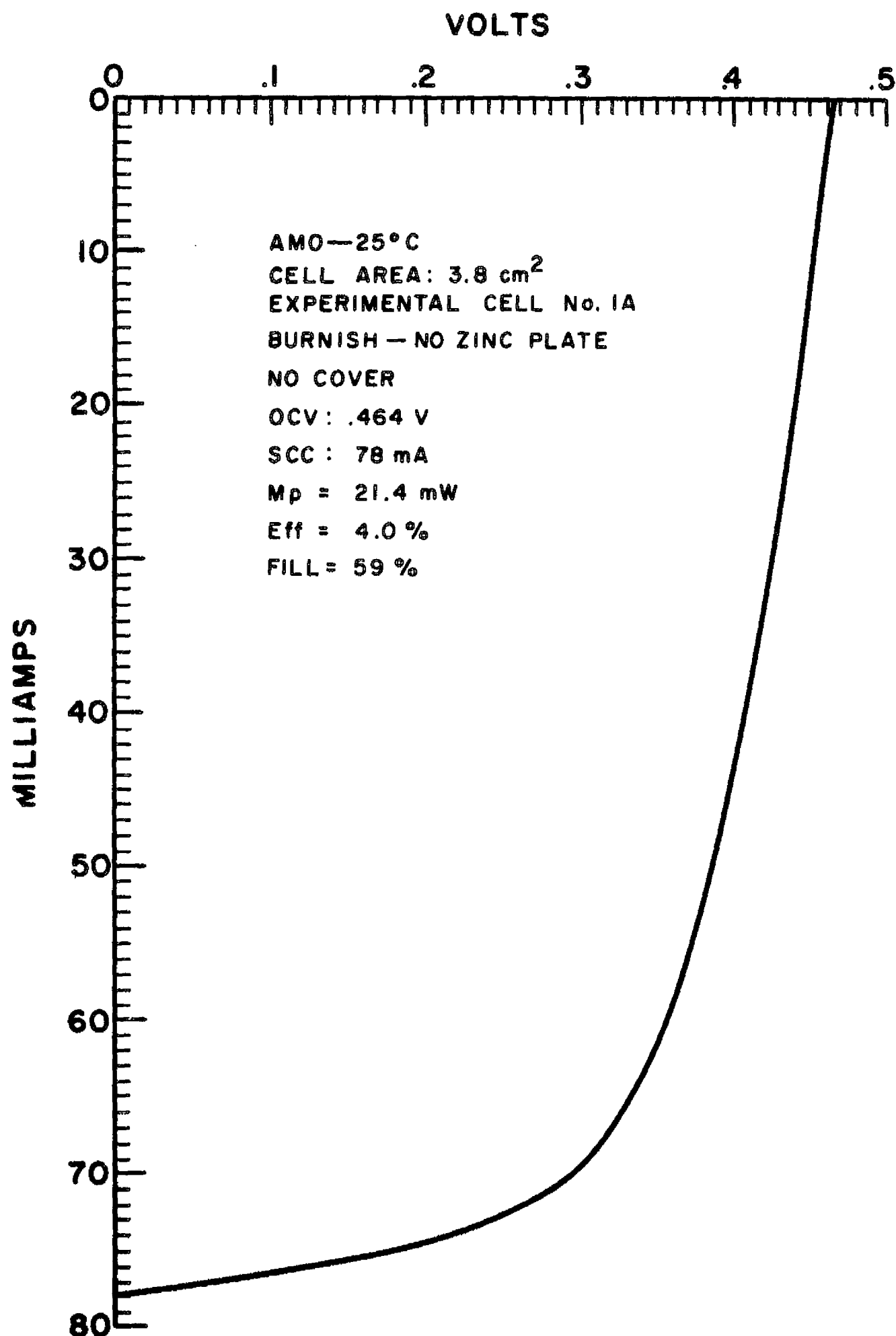
48

VOLTS

AMO—25°C

CELL AREA: 3.8 cm^2

EXPERIMENTAL CELL No. 1A

BURNISH — NO ZINC PLATE

NO COVER

OCV : .464 V

SCC : 78 mA

Mp = 21.4 mW

Eff = 4.0 %

FILL = 59 %

MILLIAMPS

FIG. 5: I-V CURVE OF CELL FORMED ON PROPRIETARY SUBSTRATE.

49

ERD 8223

FEP TEFLON COVER PLASTIC

The replacement of the Kapton cover plastic on the standard process cell with a cover material that has a transparency throughout the response spectrum of the thin film cell while maintaining the other desirable properties of the Kapton has long been desired. The principal benefit of the direct substitution of a suitable clear cover is, of course, the utilization of the energy presently being absorbed by the short-wave cut-off characteristic of the Kapton. This increase efficiency that would be realized amounts to approximately a 25% improvement under AM0 illumination. The suitability of a directly substitutable cover material, however, is determined by its resistance to in-process and end-use environmental conditions. The end-use environment has unavoidable hazards, including temperature extremes with attendant thermal shock, hard vacuum, and ultra-violet, X-ray and high energy particle radiation. In the previous reporting period, FEP Teflon* was found to reasonably fulfill these criteria, and consequent efforts to incorporate a substitute cover material in the cell have been concentrated primarily on the utilization of FEP Teflon.

The initial attempts to directly substitute FEP Teflon for Kapton, as reported previously, were discouraging because the Teflon afforded no protection against ultraviolet radiation initiated degradation of the epoxy adhesive, even in the mild ultraviolet dosage received in ground level sunlight testing. Parallel-effort programs were initiated to evaluate the ultraviolet resistance of available adhesives and to eliminate the use of separate adhesives by direct thermal fusion of Teflon to the face of the cell. Both of these efforts have continued through the current reporting period.

Thermal Fusion Bonding with FEP Teflon. - The existing process for thermally fusing FEP Teflon to the cell at the beginning of this report period was essentially a minor modification of the lamination process developed for attaching Kapton with a "B"-staging epoxy. The same lamination press was used without modification. The same post-lamination vacuum bake-out, originally intended to complete the epoxy cure, was used. Only the temperature during lamination, and consequently, the power-limited minimum time to reach lamination temperature, were altered empirically to conform with the physical conditions requisite to the formation of a cosmetically acceptable bond. The optimized lamination temperature cycle used for Teflon was found to be 2 minutes at 275°C, requiring approximately 45 minutes to reach temperature. The laminating pressure was coincidentally arbitrarily reduced to 50 psi without any apparent effect on the performance or appearance of the cell. The performance of the cells produced by this process, as well as standard process Kapton covered cells subjected to this process as a post-treatment, consistently was poorer than cells which had experienced only the standard process 20 minutes at 196 °C lamination cycle.

The possibility that the observed cell degradation being experienced was not due to the short 2 minutes required at 275°C, but rather a result of the comparatively long 45 minute interval required to heat the press to that temperature, was intriguing. Through the cooperation of NASA-Lewis, the use of a press

*Trade Mark of E. I. duPont De Nemours & Co. Inc.

capable of reaching fusion bonding temperature within 3 minutes was obtained. The press achieved this short heat-up time by the use of removable platens which permitted the cells to be arranged for lamination and evacuation externally to the press. When the press was equilibrated at the desired lamination temperature, the removable platens were rapidly slipped into the press. At the end of the pressing cycle, the platens were water-cooled to room temperature in about 10 minutes. Six cells were bonded to FEP Teflon by this procedure, 2 each at 265°C, 275°C and 283°C, all for a two-minute duration while pressurized at 100 psi. An additional pair of cells was prepared at this laboratory using the previously defined procedure (2 minutes at 275°C and 50 psi). Table XXXVII summarizes the AM0-25°C performance history of these cells.

A second group of cells was laminated at NASA-Lewis. For this group, however, the integrated time-temperature was further minimized by omitting the customary 16 hour 135°C vacuum bake-out after standard process grid lamination. All of these cells were given a 2-minute cycle at 265°C and 100 psi. Table XXXVIII summarizes the performance history of these cells.

Several conclusions were drawn on the basis of this data. First considering the initial group of cells reported in Table XXXVII, the performance of these cells was not significantly different from that of many cells previously fusion bonded. This indicated that either the integrated time-temperature during the long heat-up time was not as significant as had been anticipated, or alternatively, that there was some critical value of the integrated time-temperature which had been exceeded by both pressing cycles. The trend in the data clearly indicates a decrease in fill factor and efficiency that correlates with increasing laminating temperature. As had been consistently observed in previous fusion bonded cells, the cells which were subjected to a 16-hour 135°C vacuum bake-out showed considerable tendency to recover toward the performance level of the bare gridded cells prior to fusion bonding.

The second group of cells, those which did not receive the vacuum bake-out after application of the grids, showed improved output parameters after fusion bonding at NASA-Lewis. However, this group of cells had unusually poor output characteristics prior to bonding, efficiencies ranged from about 1-1/2% to 2-1/2%, and the recovery observed was only to performance levels considered normal for fusion bonded FEP covered cells. Otherwise, this group of cells behaved quite similarly to previously fusion bonded cells. It was concluded on the basis of this experiment that the magnitude of the integrated time-temperature below 135°C was not a critical factor in the determination of the cell's final output characteristics.

In order to evaluate the effect of an even smaller magnitude of integrated time-temperature on the performance of fusion bonded FEP covered cells, a radically different approach to the problem was attempted. In this approach, a composite consisting of the gridded cell, the FEP cover and the customary TFE parting sheets were inserted into a hermetic envelope formed by fastening 2-mil Kapton film covering both faces of an aperture cut in a 1/16" aluminum plate. Provision was made to evacuate the Kapton envelope with a mechanical pump, pressures of 100 μ to 200μ being readily achievable. A standard laminating press was modified by installation of small aluminum platens and a stop

Table XXXVII. AM0-25°C Performance of FEP Covered Cells, Heat Bonded at Various Laminating Conditions

	OCV	SCC	Fill	Eff	
224	mv	ma	%	%	
1.	461	1178	66.9	4.73	Gridded, no cover
2.	450	1161	59.4	4.05	After Lewis lam., 265°C, 2min, 100 psi
3.	450	1135	58.5	3.90	One day after lamination
4.	448	1050	56.2	3.46	7 days after lamination
5.	440	1000	55.6	3.19	20 days after lamination
6.	435	985	55.4	3.10	27 days after lamination
222					
1.	458	1248	65.6	4.87	Gridded, no cover
2.	444	1238	53.6	3.84	After Lewis lamination, 265°C, 2min, 100 psi
3.	444	1182	51.8	3.55	One day after lamination
4.	458	1210	56.2	4.06	5 days after 16 hrs, 135°C vac. bake
5.	458	1122	56.8	3.74	18 days after 16 hrs, 135°C vac. bake
6.	448	1100	55.5	3.57	25 days after 16 hrs, 135°C vac. bake
417					
1.	480	1078	67.2	4.53	Gridded, no cover
2.	455	1028	58.8	3.59	After Lewis lam. 275°C, 2min, 100 psi
3.	455	945	57.0	3.20	8 days after lamination
4.	450	900	56.8	3.00	21 days after lamination
5.	470	1077	63.5	4.18	After 16 hrs, 135°C vac. bake
6.	470	1019	62.0	3.88	6 days later
416					
1.	474	1075	68.9	4.58	Gridded, no cover
2.	446	1030	54.4	3.26	After Lewis Lam, 275°C, 2min, 100 psi
3.	440	930	53.6	2.86	8 days after lamination
4.	431	860	51.0	2.46	21 days after lamination
5.	430	848	50.8	2.42	28 days after lamination
414					
1.	474	1125	67.2	4.62	Gridded, no cover
2.	450	1060	56.8	3.54	After Clevite lam. 275°C 50 psi
3.	460	1010	53.2	3.22	One day later
4.	460	900	47.6	2.57	7 days later
5.	453	865	47.5	2.43	20 days later
6.	453	850	49.0	2.46	27 days later
221					
1.	458	1145	66.8	4.44	Gridded, no cover
2.	442	1050	52.5	3.18	After Clevite lam, 275°C 50 psi
3.	454	990	45.0	2.65	One day later
4.	460	1080	56.7	3.67	5 days after 16 hrs, 135°C vac. bake
5.	460	1020	56.5	3.45	18 days after 16 hrs, 135°C vac. bake
6.	458	990	54.9	3.25	25 days after 16 hrs, 135°C vac. bake
415					
1.	470	1175	68.2	4.90	Gridded, no cover
2.	425	1065	41.7	2.46	After Lewis lam. 283°C, 2min, 100 psi
3.	420	940	40.2	2.07	8 days after lamination
4.	415	855	38.0	1.76	21 days after lamination
5.	453	1110	56.1	3.68	After 16 hrs, 135°C vac. bake
6.	440	1052	51.0	3.08	6 days later
223					
1.	462	1175	66.0	4.68	Gridded, no cover
2.	430	785	40.0	1.76	After Lewis lam, 283°C, 2min, 100 psi
3.	425	750	39.6	1.65	8 days after lamination
4.	422	690	40.8	1.55	21 days after lamination
5.	419	665	38.8	1.41	28 days after lamination

Table XXXVIII. AM0-25°C Performance of FEP Covered Cells with Minimum
High Temperature Exposure

	OCV	SCC	Fill	Eff	
156	mv	ma	%	%	
1.	429	1020	37.6	2.14	Gridded, no cover
2.	468	1240	49.3	3.72	1 day after Lewis lam. 265°C, 2min, 100 psi
3.	468	1110	48.5	3.29	5 days after Lewis lam.
4.	470	1322	55.0	4.46	After 16 hrs, 135°C vac. bake
5.	469	1277	54.5	4.25	1 day later
6	469	1330	54.9	4.45	After 2nd 16 hr 135°C vac. bake
7.	469	1230	53.2	4.00	7 days later
157					
1.	421	1001	37.6	2.07	Gridded, no cover
2.	470	1240	52.5	3.98	1 day after Lewis lam, 265°C, 2min, 100 psi
3.	470	1150	51.8	3.65	5 days after Lewis lam.
4.	468	1059	49.0	3.17	15 days after Lewis lam.
158					
1.	430	1025	38.3	2.20	Gridded, no cover
2.	465	1025	37.6	2.34	4 days after Lewis lam. 265°C, 2min, 100 psi
3.	462	860	38.0	1.97	14 days after Lewis lam.
159					
1.	430	1050	40.0	2.36	Gridded, no cover
2.	468	1160	44.8	3.17	4 days after Lewis lam, 265°C, 2min, 100 psi
3.	465	970	43.8	2.58	14 days after Lewis lam.
151					
1.	403	678	40.6	1.45	Gridded, no cover
2.	459	1200	42.6	3.06	4 days after Lewis lam, 265°C, 2min, 100 psi
3.	450	908	37.5	2.00	After 2 min @ 250°C air bake
4.	450	839	37.2	1.83	1 day after 2 min @ 250°C, air bake
5.	466	1220	51.3	3.80	After 16 hrs, 135°C vac. bake
6.	452	1130	46.9	3.13	7 days after 16 hrs, 135°C vac. bake
152					
1.	420	1085	37.4	2.22	Gridded, no cover
2.	466	1202	42.5	3.10	One day after Lewis lam, 2min, 265°C
3.	466	1030	41.7	2.62	5 days after Lewis lam.
4.	470	983	41.1	2.48	7 days after Lewis lam.
5.	464	1308	41.2	3.25	After 20 min, @ 196°C, 100 psi lam cycle
6.	470	1380	45.5	3.86	After 16 hrs, 135°C vac bake
7.	470	1248	45.0	3.44	6 days later
153					
1.	423	1001	38.9	2.15	Gridded, no cover
2.	460	1208	49.9	3.60	One day after Lewis lam. 2min, 265°C
3.	455	1062	48.3	3.06	5 days after Lewis lam.
4.	453	928	40.3	2.20	After 2 min. 250°C air bake
5.	451	897	39.8	2.10	One day later
6.	469	1193	55.4	4.05	After 16 hrs, 135°C vac. bake
7.	460	1128	53.0	3.59	7 days later
154					
1.	419	803	36.6	1.60	Gridded, no cover
2.	461	1280	54.0	4.16	One day after Lewis lam. 2min, 265°C
3.	465	1165	54.2	3.83	5 days after Lewis lam.
4.	456	1343	54.8	4.46	After 16 hrs. 135°C vac. bake
5.	469	1318	55.3	4.45	One day later
6.	469	1330	54.0	4.39	After 2nd 16 hrs, 135°C vac. bake
7.	469	1240	55.0	4.17	7 days later
155					
1.	410	742	39.4	1.56	Gridded, no cover
2.	469	1320	49.5	3.99	One day after Lewis lam, 2min, 265°C
3.	470	1120	50.2	3.61	5 days after Lewis lam.
4.	470	1130	47.8	3.30	7 days after Lewis lam.
5.	459	1398	43.8	3.65	After 20 min. 196°C, 100 psi lam. cycle
6.	466	1362	47.3	3.91	After 16 hrs 135°C vac. bake
7.	470	1300	49.7	3.96	6 days after

assembly which permitted rapid alignment of the Kapton covered aperture with the platens. The lower platen was covered with a sheet of 1/16" silicone rubber.

In operation, the press platens were first equilibrated at the desired laminating temperature with the platens closed. A laminating cycle then consisted of opening the platens, inserting the hermetic envelope containing the cell into the press in register with the platens, closing the platens with about 50 psi pressure, and then opening the press and removing the envelope at the end of the desired laminating time. Because the hermetic envelope and its contents within the aperture had almost insignificant thermal masses, the temperature of the portion of the assembly that came in contact with the platens rapidly equilibrated to the platen temperature. Lamination cycles that included a thermocouple in contact with the cell being covered demonstrated that only 3 seconds were required to reach within 10°C of equilibrium temperature. Typical cooling times after removal from the press were about 20 seconds to reach below 100°C.

A series of trial laminations of FEP Teflon to gridded cells that covered a range of process conditions that extended from 10 seconds to 240 seconds duration were run at temperatures from 260°C to 300°C. In the course of these trial laminations, it was found that the cumulative pressing time could be minimized by incorporating a very brief preheat to a temperature just below the fusing point of the FEP, followed by about a 3-second pressure release. The press was then closed again for the duration of the main lamination strike. The brief preheat has been rationalized on the assumption that it permits the cell and cover to outgas at a temperature near the maximum process temperature, and furthermore, allows sufficient time for the gases evolved to be pumped away from the cell before the cover becomes sealed in place. It was concluded on the basis of this test and the experience of many subsequent laminations, that a broad range of time-temperature conditions will produce mechanically and cosmetically acceptable fusion bonded FEP Teflon covers. Minimally acceptable cells were fabricated at 270°C with a 2-second preheat strike followed by a 20-second lamination strike. Full strength bonds were achieved by a 2-second-20-second double strike at 280°C, which was adopted as standard operating procedure. When subjected to this cycle, the cell being covered was heated to temperatures above 196°C, the maximum temperature experienced during the conventional epoxy lamination cycle, for only about 25 seconds accumulated exposure. This minimized time-temperature exposure suggested the descriptive designation given to the process: flash bonding.

Mechanical and Electrical Performance of Flash Bonded FEP Teflon Covered Cells. - The bonds produced by the flash bonding procedure were generally mechanically sound. The usual failure plane upon attempt to peel back the cover was the Kapton-Pyre-ML interface. Subjected to "T"-pull tests, the FEP Teflon leg of the specimen usually tore before any disturbance of the bond area was observed. The only observed areas of weakness of the bond occurred where the cover necessarily was bonded directly to the silver-Pyre-ML at the negative edge of the cell and directly to a comparatively broad expanse of gold-plated copper along the positive edge. Adhesion to these problem areas was solved by the

application of Allied Chemical's KH-1 primer to these zones followed by a 10-minute primer cure at 90°C in vacuum prior to flash bonding.

The electrical performance of the flash bonded cells showed significant improvement over that previously experienced with the slower fusion bonding technique. A group of 24 of the earliest electrically sound cells covered by flash bonding had an average AMO-25°C efficiency of 4.75%, with the best cell of the group measuring 5.2%. The flash bonding process regularly produced cells having greater efficiency after the cover was attached than was measured on the bare gridded cells, the reverse of the situation observed in cells produced by slower fusion bonding techniques. The initial performance of a later group of flash bonded FEP Teflon cells prepared for use in the controlled environmental exposure test described later is shown in Table XXXIX. This was the largest group of cells simultaneously committed to the flash bonding process, and consequently, this electrical performance data is probably the only data which might be classified as typical. None of the other flash bonded cells fabricated in the reporting period showed significantly different electrical characteristics.

Room Temperature Stability of Flash Bonded FEP Teflon Covered Cells. - While the level of the output parameters of the flash bonded cells was good, the stability was not. A rate of degradation similar to that of the cells covered by the slower fusion bonding methods was observed in the first flash bonded specimens. In pursuit of the idea that the flash bonded cells might have had an adjustment period of high instability which might have been moderated by the 16-hour 135°C vacuum bake-out that seemed to have had a beneficial influence on earlier fushion bonded cells, an experiment was conducted in which the time dependent performance of these cells was determined. Zero-time was defined as the moment of removal from the last high temperature process. In the case of flash bonded cells not subjected to bake-out, zero-time was the time of removal from the flash bonding press. In the case of flash bonded cells receiving the 16-hour bake-out, zero-time was established by the moment of removal from the bake-out oven. In either case, the first I-V curve was obtained in the shortest practical interval from zero-time, and additional curves were obtained at roughly half decade time intervals.

Shortly after initiating this experiment with the flash bonded cells, two groups of standard process Kapton cells were added to the experiment. One group was given the 16-hour bake-out, zero-time being determined as in the parallel group of flash bonded cells. The other group was not given the bake-out, and zero-time was defined by the moment at which cooling water began to circulate in the laminator platens during the standard Kapton cover plastic lamination cycle.

Figures 6 and 7 summarize the time-dependent variations in maximum power observed in all of the cells in the experiment. Figures 8, 9, 10, and 11 show the normalized electrical parameters of one cell from each group. Figures 12 and 13 show selected I-V curves from the first day of testing of cell 305-751B from which were obtained the data used to construct Fig. 8. Figure 14 shows the 1-day I-V curve for cell 307-146D which is followed in Fig. 9. The adjustments were small in this cell during the initial week. Figures 15 and 16 show selected I-V curves from the first several days of the cells plotted in Figs. 10 and 11, respectively.

TABLE XXXIX.

24 Flash Bonded FEP Teflon Covered Cells.
Prepared for Controlled Environment Exposure Test.
Measured 20-Days After Fabrication

Simulated AM0 and 25°C Conditions

Cell No.	OCV V	SCC A	V_{mp} V	I_{mp} A	MP W	Eff. %	Fill %
330-410	.488	1.145	.375	.990	.371	4.84	66.4
334-347A	.492	1.090	.370	.960	.355	4.64	66.2
334-741A	.485	1.105	.365	.990	.362	4.72	67.5
334-742A	.485	1.142	.365	1.010	.369	4.82	66.5
334-743A	.485	1.110	.370	.980	.363	4.73	67.2
334-744A	.480	1.135	.360	1.010	.364	4.75	66.8
334-745A	.478	1.210	.350	1.050	.368	4.80	63.5
334-746A	.482	1.140	.365	1.010	.369	4.80	67.1
334-748A	.480	1.150	.365	1.000	.365	4.76	66.0
334-749A	.490	1.105	.340	.925	.314	4.10	58.0
336-855H	.460	1.280	.330	1.020	.337	4.40	57.2
336-858H	.478	1.005	.355	.835	.297	3.87	61.6
336-859H	.480	1.080	.365	.880	.321	4.19	62.0
340-765C	.488	1.095	.370	.950	.351	4.58	55.6
340-766C	.490	1.080	.370	.930	.344	4.49	65.0
340-767C	.480	1.010	.355	.885	.314	4.10	64.8
340-768C	.490	1.030	.375	.890	.334	4.35	66.1
340-769C	.480	1.035	.365	.840	.306	4.00	61.7
341-254B	.485	1.022	.365	.910	.332	4.34	67.0
341-255B	.470	1.245	.350	1.070	.375	4.89	64.0
341-256B	.475	1.190	.355	1.030	.366	4.78	64.6
341-257B	.490	1.035	.370	.920	.340	4.44	67.^
341-258B	.475	1.170	.360	1.020	.368	4.80	66.0
341-259B	.490	1.062	.370	.940	.348	4.54	66.6
Average	.482	1.111	.362	.960	.347	4.53	64.8
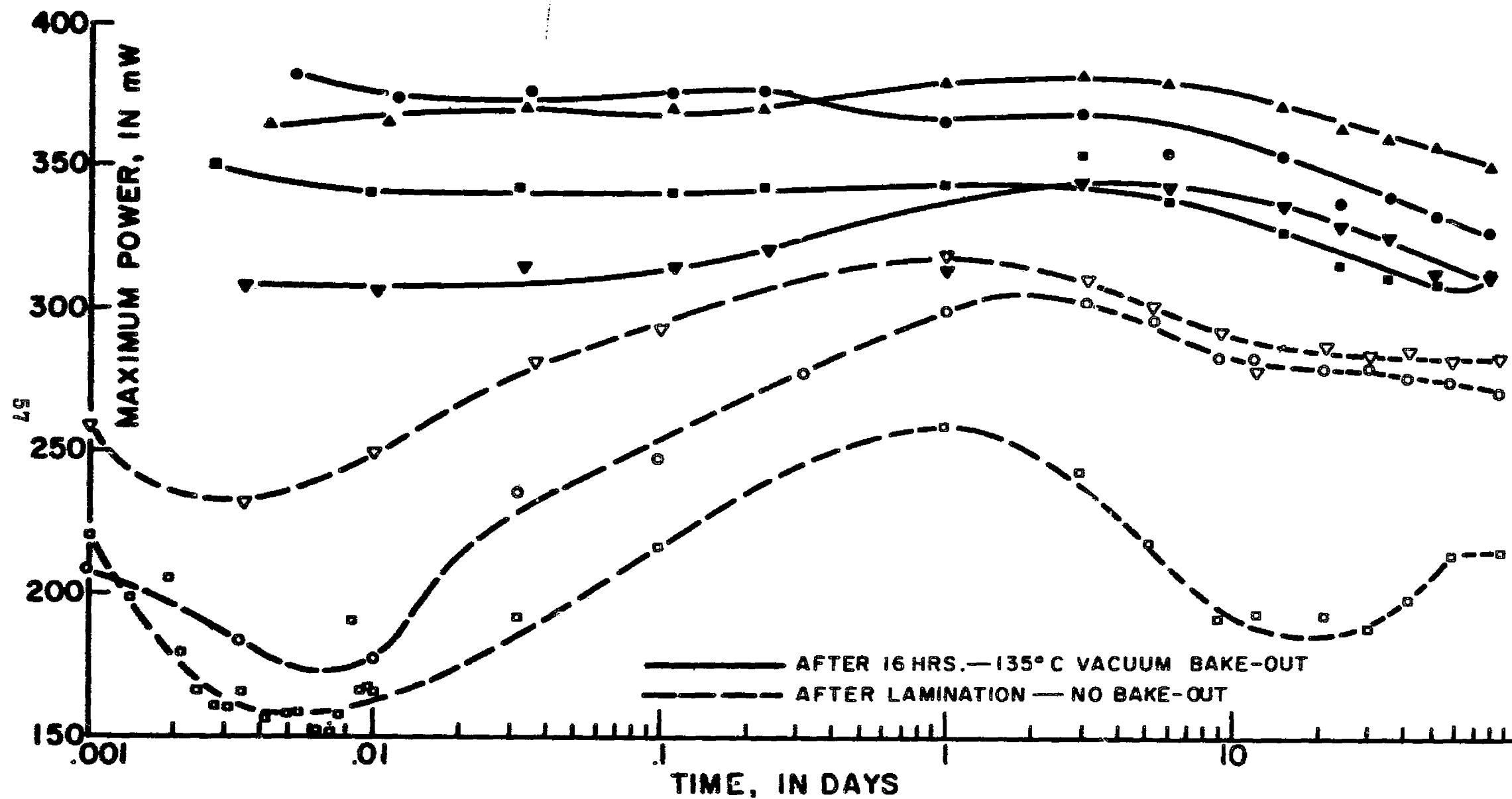
FIG. 6: TIME DEPENDENT VARIATION IN MAXIMUM POWER—FEP FLASH BONDED CELLS.

Legend:
AFTER 16 HRS.—135°C VACUUM BAKE-OUT
AFTER LAMINATION — NO BAKE-OUT

Y-axis: MAXIMUM POWER, IN mW (150, 200, 250, 300, 350, 400)
X-axis: TIME, IN DAYS (.001, .01, .1, 10)

57

ERD 8224
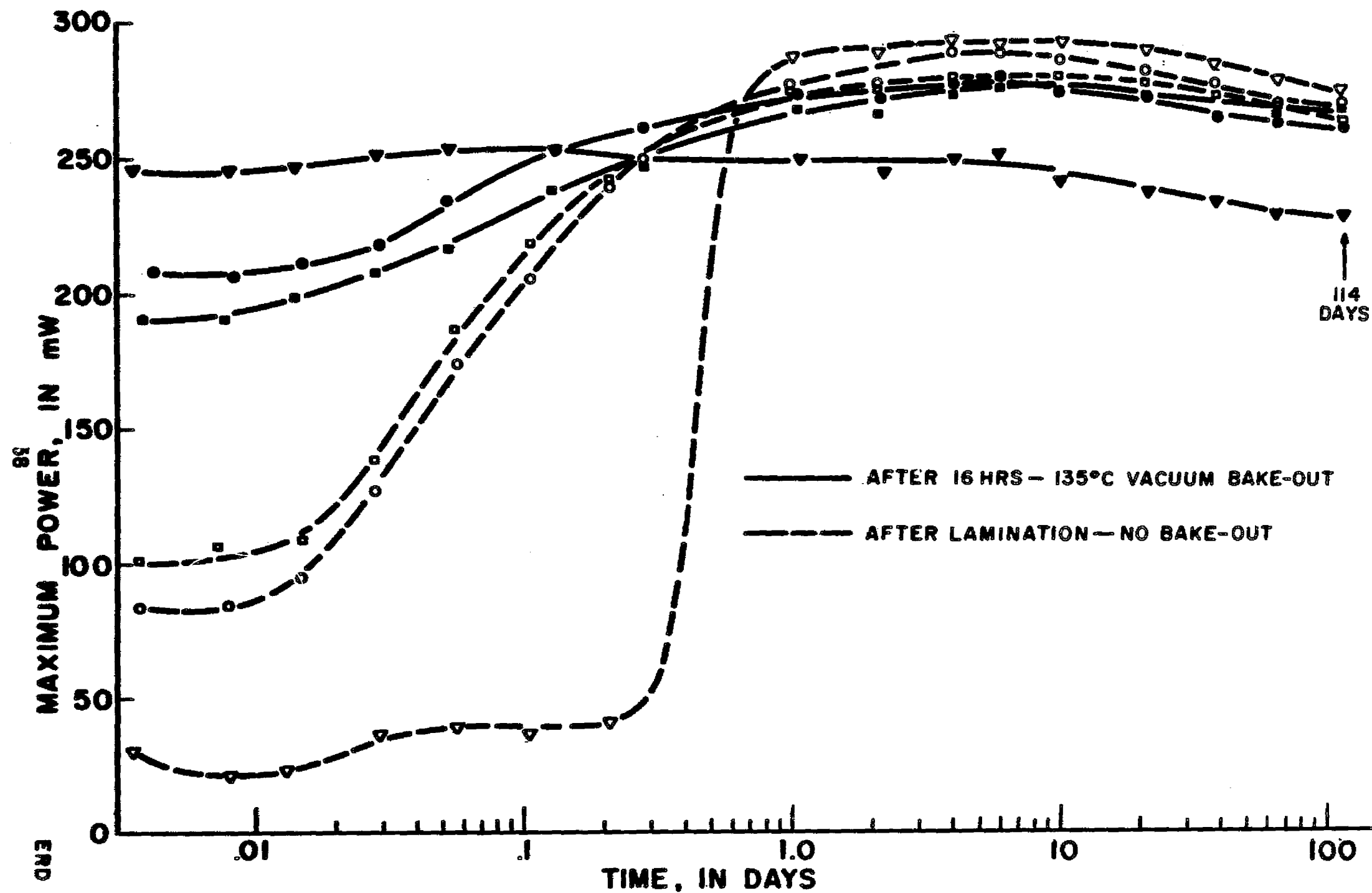
FIG. 7 : TIME DEPENDENT VARIATION IN MAXIMUM POWER — KAPTON CELLS.

AFTER 16 HRS — 135°C VACUUM BAKE-OUT

AFTER LAMINATION — NO BAKE-OUT

114 DAYS

MAXIMUM POWER, IN MW

TIME, IN DAYS

ERD 8225

38
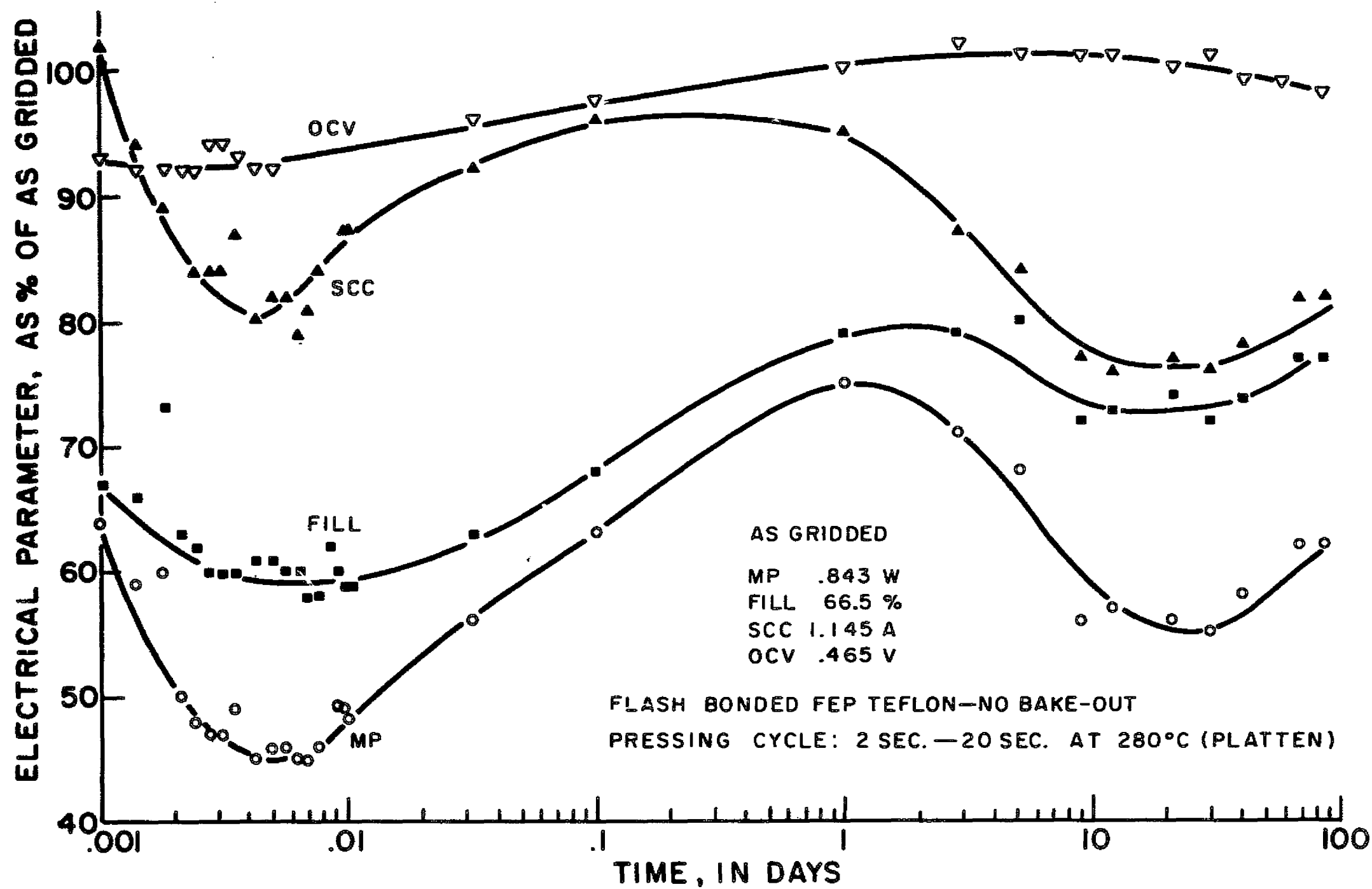
FIG. 8: CELL 305751 B TIME DEPENDENT VARIATION OF OUTPUT PARAMETERS.

59
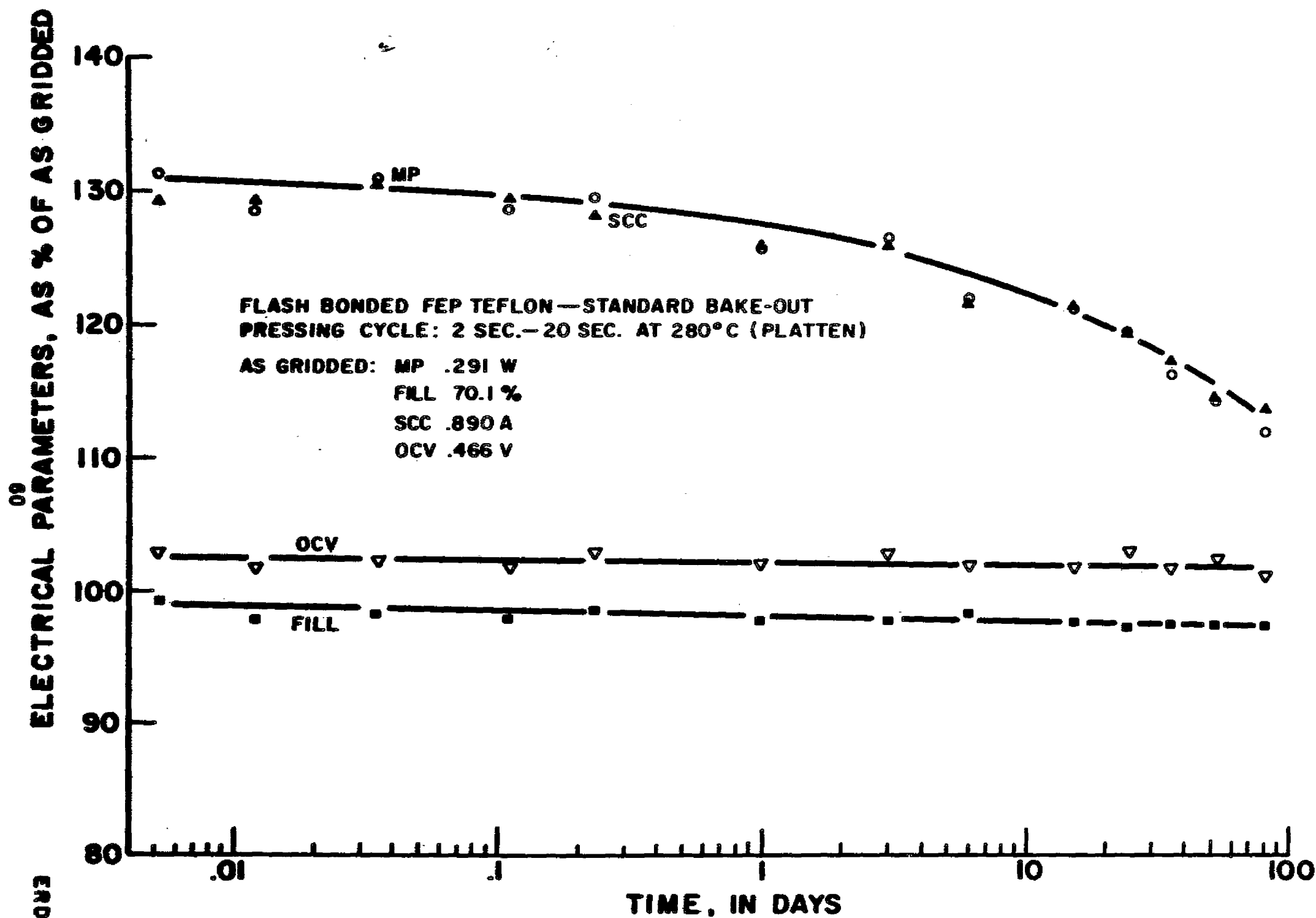
FIG. 9: CELL 307146 D TIME DEPENDENT VARIATION OF OUTPUT PARAMETERS.

Chart annotations:

ELECTRICAL PARAMETERS, AS % OF AS GRIDDED (vertical axis, 80 to 140)

TIME, IN DAYS (horizontal axis, .01 to 100)

FLASH BONDED FEP TEFLON—STANDARD BAKE-OUT
PRESSING CYCLE: 2 SEC.—20 SEC. AT 280°C (PLATTEN)

AS GRIDDED: MP   .291 W
             FILL 70.1 %
             SCC   .890 A
             OCV   .466 V

Curve labels: MP, SCC, OCV, FILL
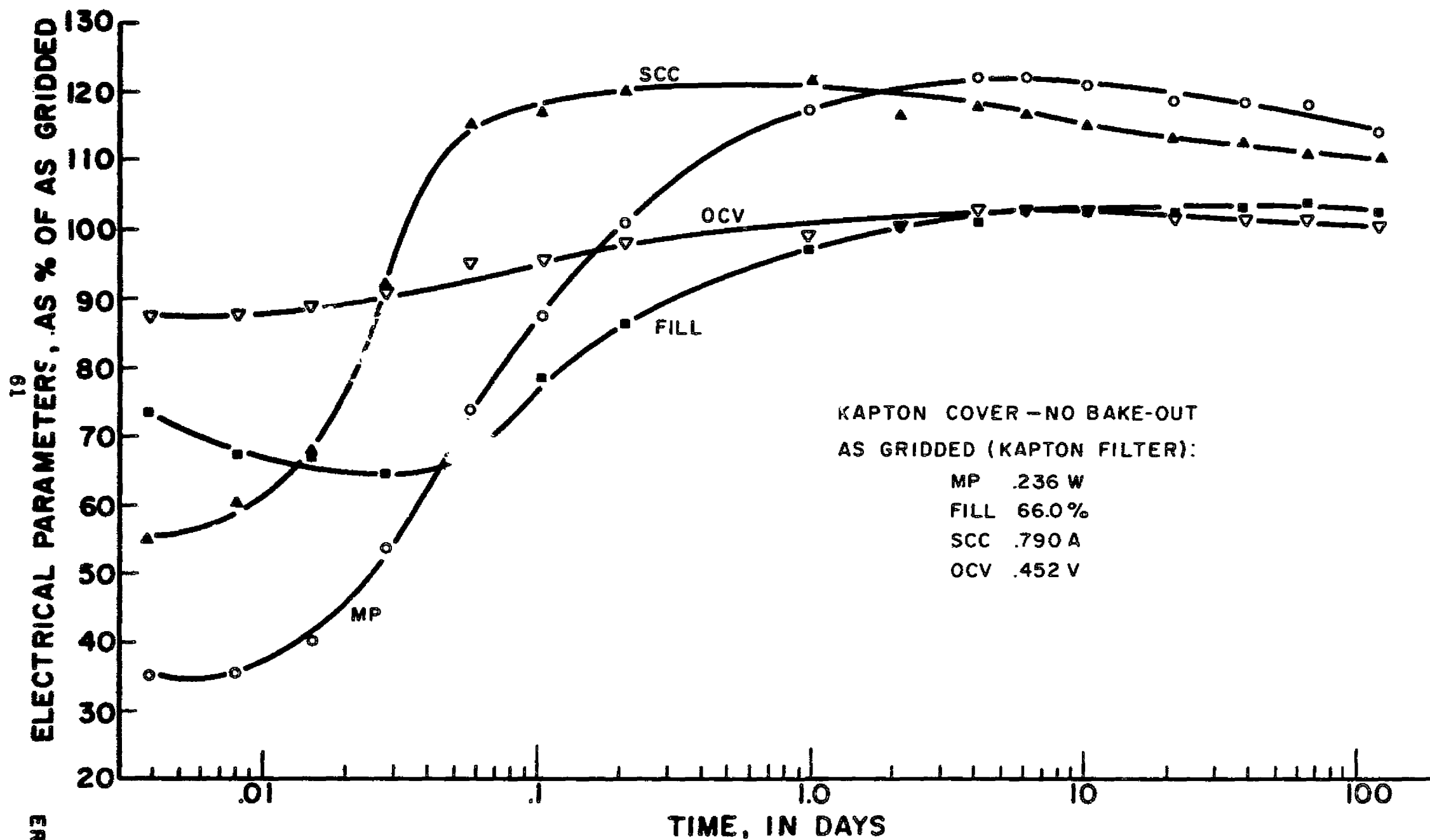
FIG. 10: CELL 315565 TIME DEPENDENT VARIATION OF OUTPUT PARAMETERS.
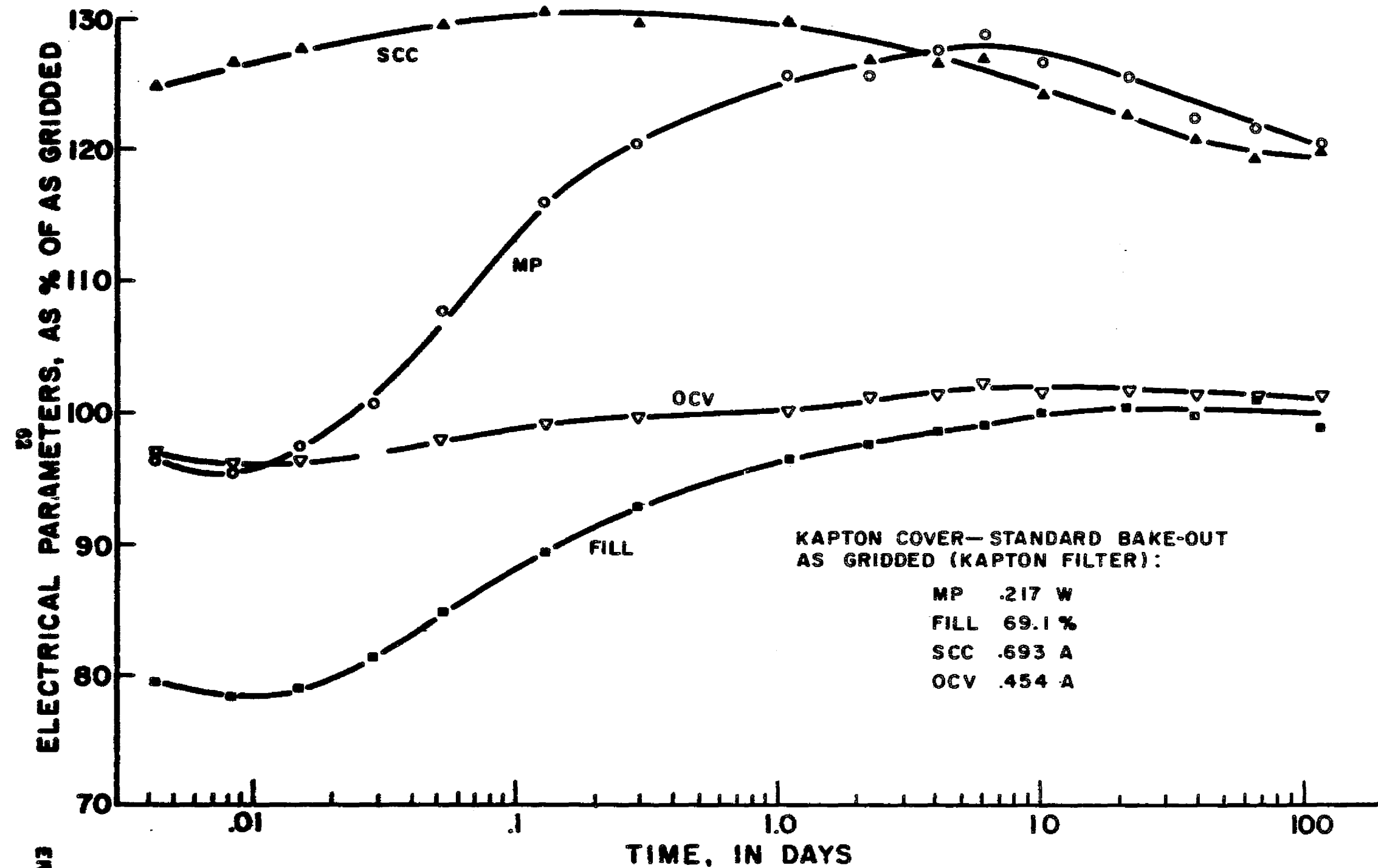
FIG. 11: CELL 315562 C TIME DEPENDENT VARIATION OF OUTPUT PARAMETERS.
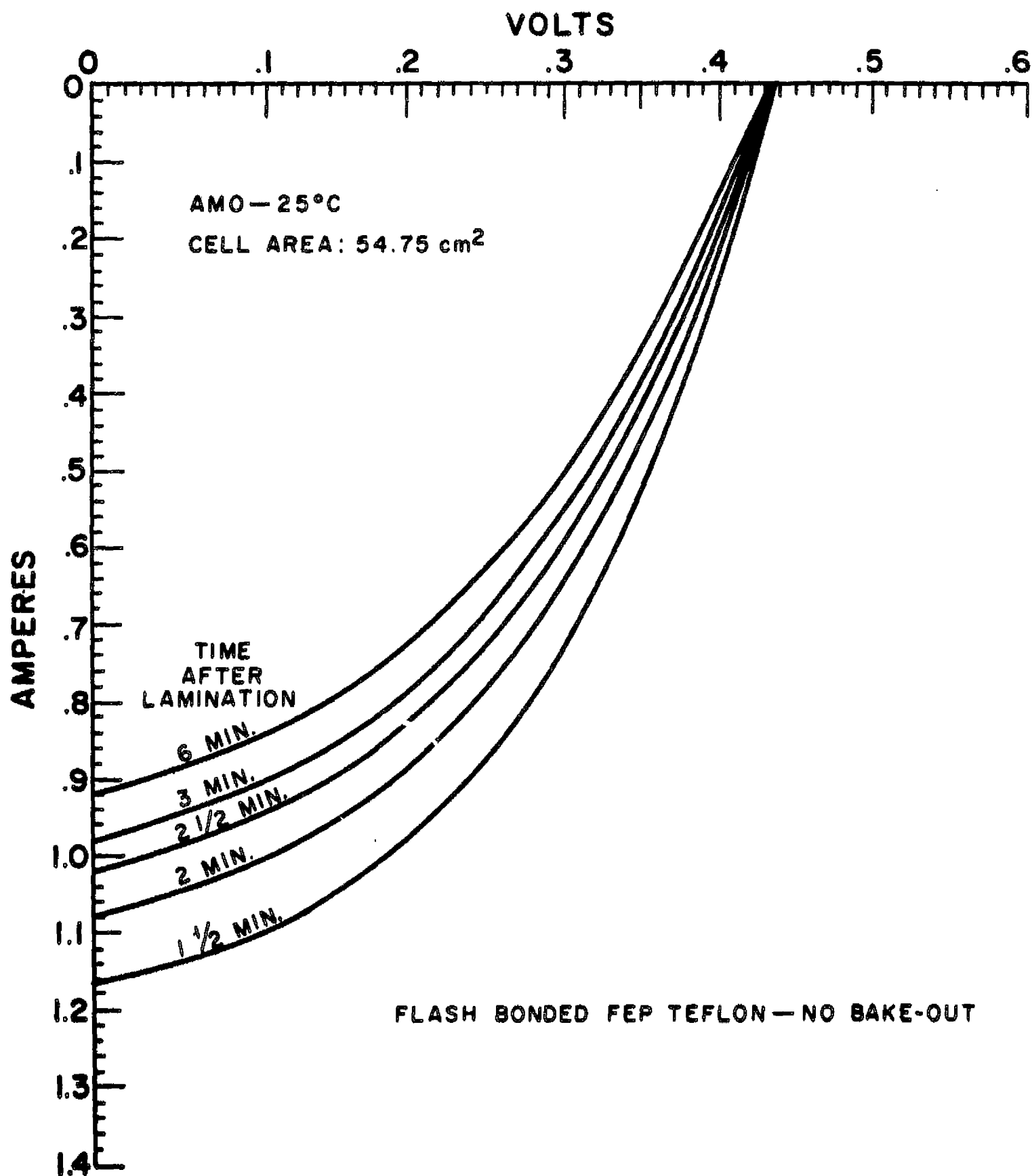
FIG. 12: CELL 305751B SELECTED I-V CURVES FROM THE INITIAL 6 MINUTES OF AGING.

ERD 8230

VOLTS

AMO — 25°C
CELL AREA : 54.75 cm²

TIME
AFTER
LAMINATION:

9 MIN.
6 MIN.
15 MIN.
46 MIN.
144 MIN.
24 HRS.

FLASH BONDED FEP TEFLON — NO BAKE-OUT

FIG. 13: CELL 3057518 SELECTED I-V CURVES FROM
6 MINUTES THROUGH 4 HOURS OF AGING.

ERD 8231
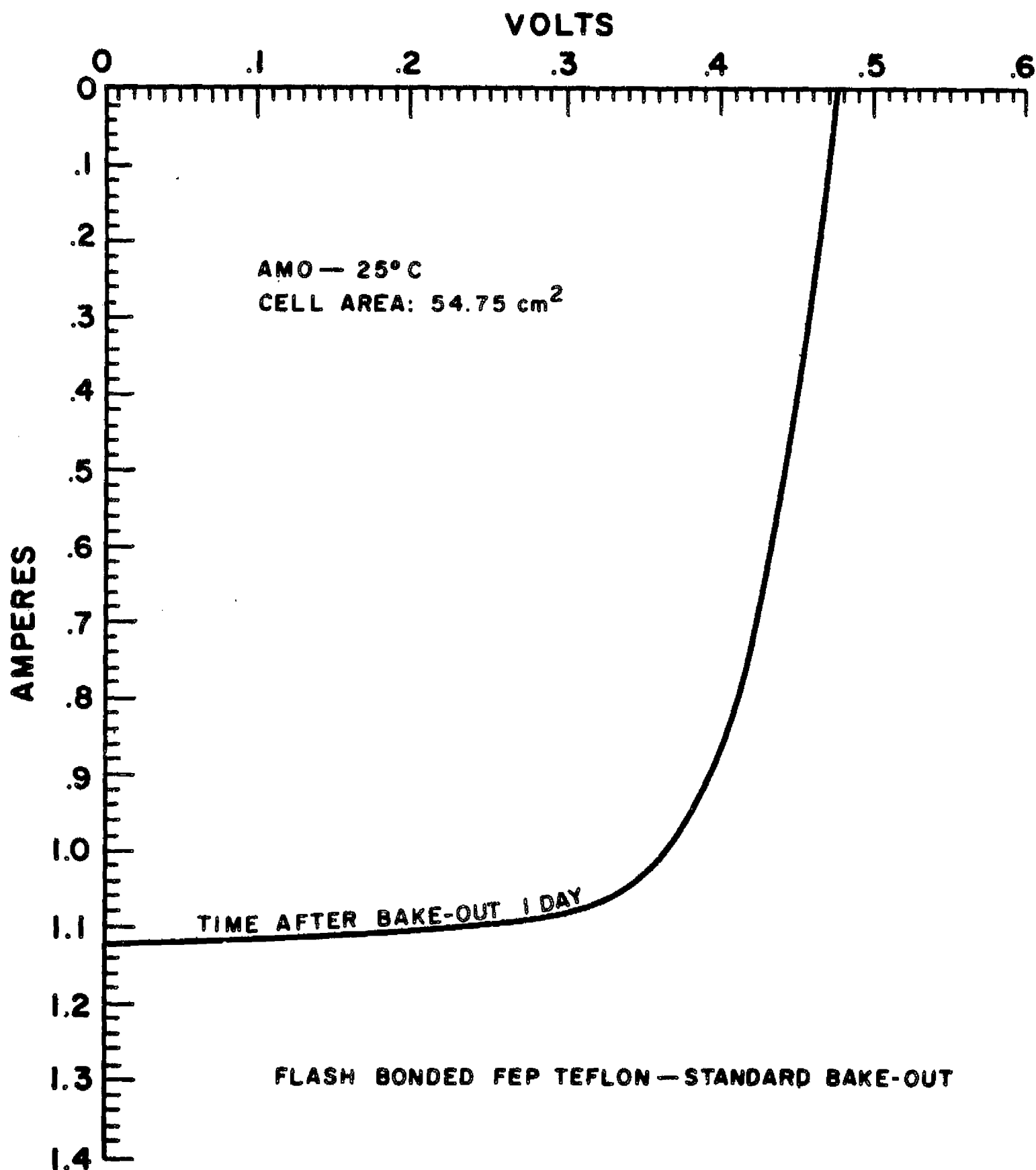
FIG. 14: CELL 307146D AGED I DAY.

ERD 8232
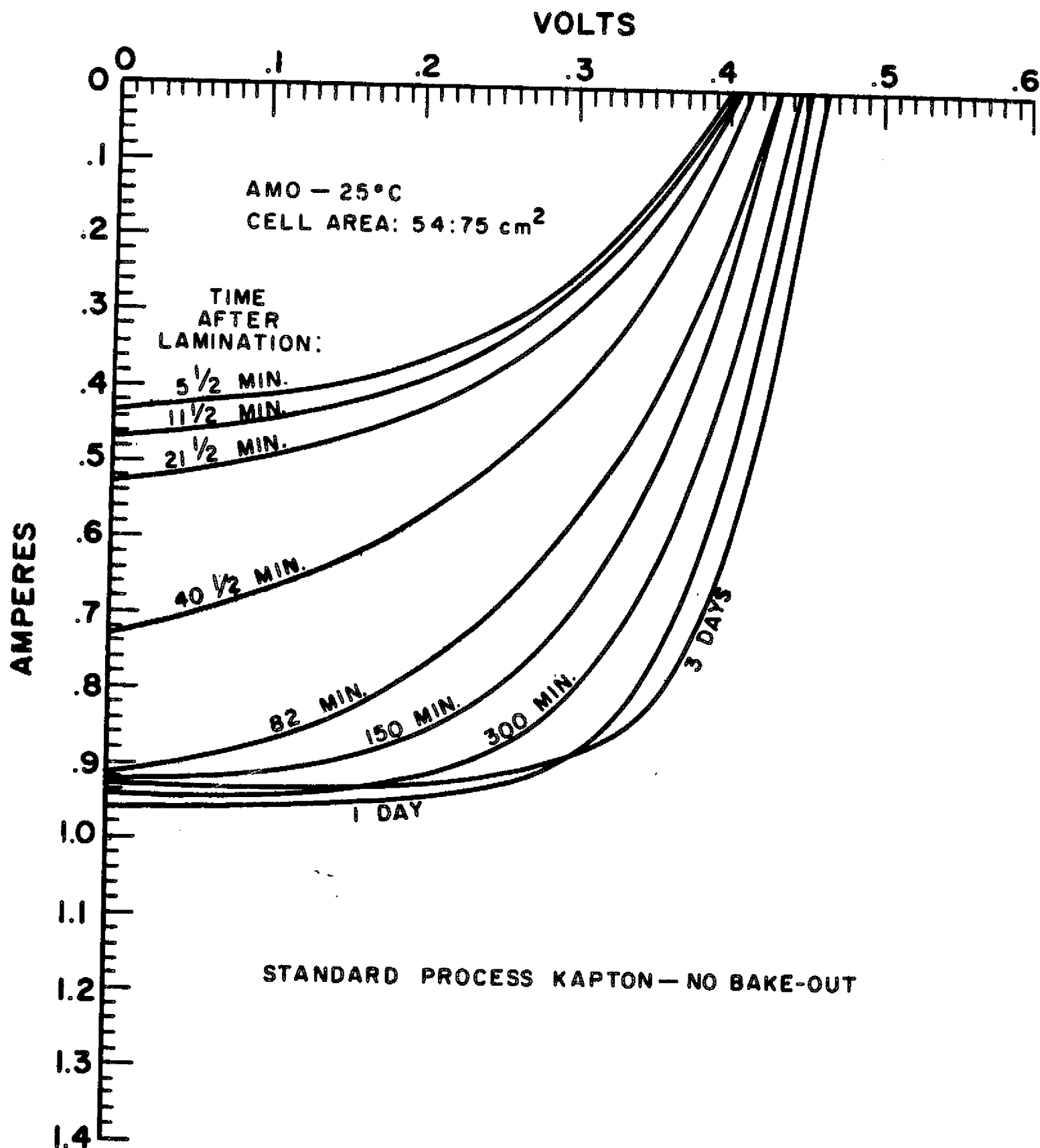
FIG. 15: CELL 315565C SELECTED I-V CURVES FROM THE INITIAL 3 DAYS OF AGING.

66
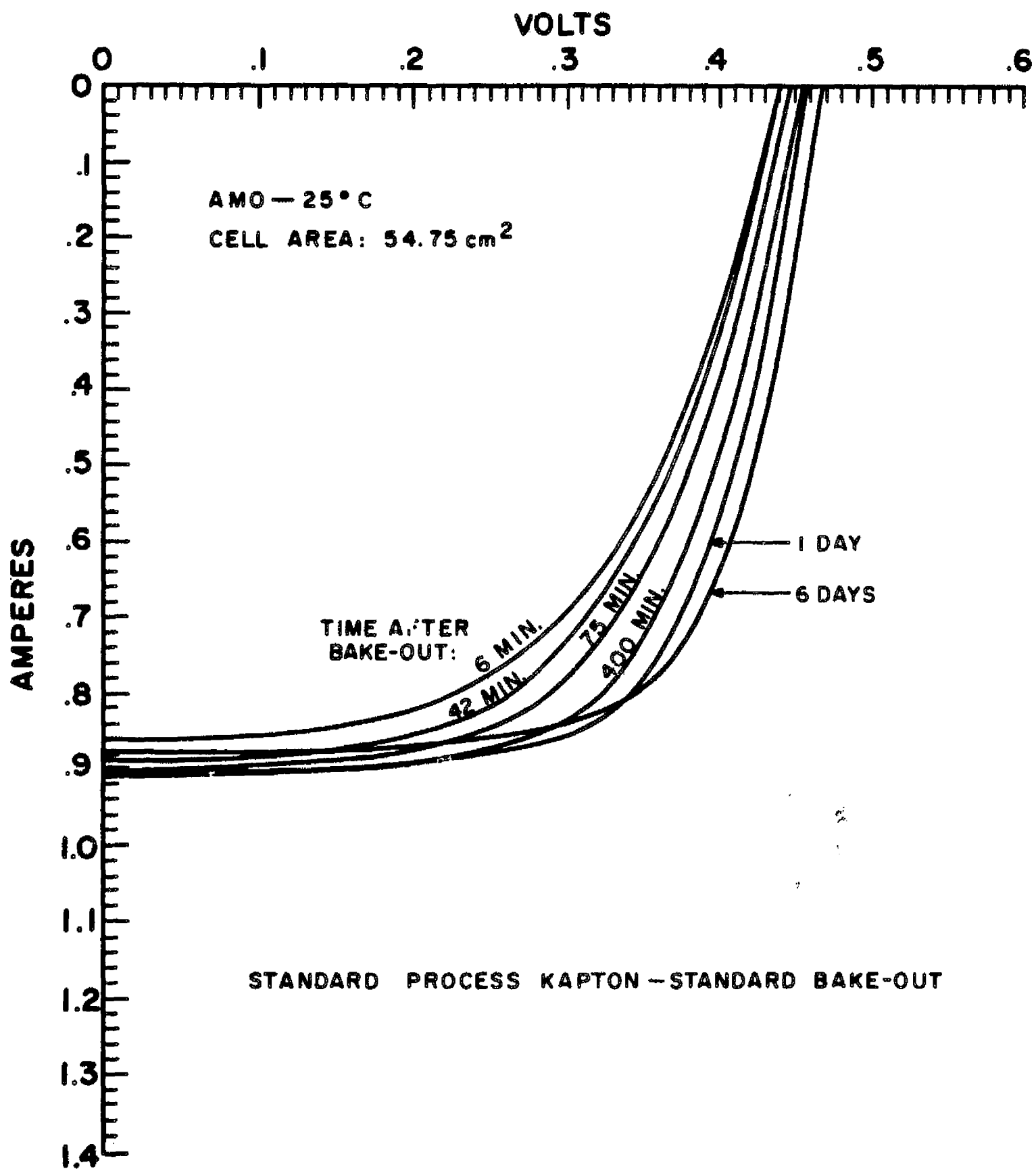
FIG. 16: CELL 315562 C SELECTED I-V CURVES FROM
THE INITIAL 6 DAYS OF AGING.

ERD 8234

Both the flash bonded FEP Teflon and standard process Kapton cells which received the customary 16-hour 135°C vacuum bake-out appeared to make no rapid adjustments, but gradually increased in output to reach a maxiimum in about 3 to 6 days. At about this time the short circuit current, which had peaked between 0.1 and 1.0 days and had begun to decline, began to influence the maximum power. From 10 days on, the degradation tended to stabilize to a steady rate, with the Teflon covered cells degrading faster than the Kapton ones. This behavior was substantiated by the observation of similar effects during the first 10 days of adjustment on another group of 5 standard process Kapton covered Class I cells.

The group of flash bonded FEP Teflon cells which did not receive the bake-out showed more pronounced adjustments during the observation period and tended to reach peak power about 1 day after lamination. Due to the rapid cooling inherent in the flash bonding process, the electrical parameters of these cells could be measured within 1-1/2 minutes after exposure to the laminating temperature. This permitted the first observation of the degradation of output parameters that occurs during the critical first 5 to 7 minutes after the conclusion of the high temperature exposure. Since these cells never returned to the output level measured before applying the cover, while the flash bonded cells subjected to the vacuum bake-out regularly showed at least a slight improvement in the same parameters, it is believed that some damage is done to the cell by the brief high temperature lamination cycle, but the damage is of such a nature that it is subject to removal by an annealing procedure similar to the unoptimized 135°C-16-hour vacuum bake-out.

The Kapton cells which did not receive the bake-out displayed a similar initial adjustment period, but even more dramatically. The first measurement of electrical parameters after removal from the lamination press, usually about 5 minutes after the initiation of water-cooling, showed the maximum power to be less than half of recovered value a day later. Since the cells could not be tested earlier than 5 minutes after high temperature exposure, the minima observed as in the case of the flash bonded cells was not well-defined. Even more surprising was the observation that these cells ultimately adjusted to a higher level of maximum power than did the Kapton cells which received bake-out, contrary to the behavior observed in the flash bonded FEP Teflon cells.

The mechanism responsible for the observed adjustment effects has not been identified. The role of Cu_2S, which undergoes numerous phase changes[3] in the temperature range experienced in the flash bonding as well as in standard process lamination, with several of the phases formed being metastable, must be considered a possible source of the mechanism causing the adjustment effects. A significant and reversible sudden change in the short-circuit current of the CdS thin film solar cell that correlated with one of these phase changes has been reported.[4]

In addition, the effects of the adsorption and desorption of atmospheric constituents on the barrier layer as a consequence of the high temperature vacuum exposures followed by cooling either in air or in vacuum must also be considered as possible causes of the observed effects.

Controlled Environment Degradation of Flash Bonded FEP Teflon Covered Cells. - Early results from flash bonded FEP Teflon cells placed in the moisture storage test were disturbing. The flash bonded cells were showing more rapid degradation in this test than were the standard process Kapton cells, despite the manufacturer's specifications which indicated that FEP Teflon should be about 13 times less permeable to water vapor than Kapton of the same thickness.

A water vapor permeability test was conducted comparing flash bonded FEP Teflon with Kapton and several other plastic films. The test method used was the pouch method, modified to utilize available equipment. A measured quantity of silica gel was double sealed into a pouch constructed of the films to be tested and subjected to 24 hours exposure in a constant temperature/humidity chamber maintained at 35°C and 95% relative humidity. The weights of the pouches before and after exposure along with the area and thickness of film used to construct the pouch permitted calculation of water vapor permeability on a per mil thickness basis. The results are shown in Table XL. The measured permeability of the flash bonded FEP Teflon was nearly 40 times greater than the manufacturer's specification. It is believed that the process of flash bonding damaged the film in some way that accounts for this significant difference.

Table XL. Water Vapor Permeability Test Environment: 35°C/96% Relative Humidity

Plastic Film	Form	Permeability g/100 in^2/mil/24 hrs
Aclar 33C	1 mil film	0.07 or less
Mylar	1 mil film	0.79
Mylar	Bilaminate: 2, 1 mil films with 1 mil epoxy	1.1
Polyethylene	0.7 mil film	1.1
Kapton	1 mil film	1.8
Kapton	Bilaminate: 2, 1 mil films, with 1 mil epoxy	1.8
FEP Teflon	Bilaminate: 2, 1 mil films, flash bonded	15.0

To further investigate the humidity dependent degradation, as well as to attempt to gain some insight into the role of atmospheric oxygen in that degradation, a controlled environment system was assembled. This system permitted

exposure of cells to the 8 different storage conditions as shown in the bottom row of Table XLI.

Table XLI. Controlled Environment Storage Conditions.

Environment	Air				Nitrogen			
Temperature	22°C		40°C		22°C		40°C	
Relative Humidity	< 5%	> 95%	< 5%	> 95%	< 5%	> 95%	< 5%	> 95%

The experimental apparatus consisted of two gas trains, one driven by dry nitrogen and the other by compressed air.

A simplified diagram of one of the gas trains is shown in Fig. 17. The regulators, valving and traps found necessary to control the gas flow and prevent the water bubblers from backing up are not shown. Both gas trains were operated with 50 ml/hour flow rate, corresponding to about a 6 minute refreshment rate for the gas in each chamber. The cold traps in the gas train operated on compressed air were adjusted to avoid condensation of the oxygen content.

Specimens used in this test consisted of 2 flash bonded FEP Teflon covered cells and 3 standard process Kapton covered cells per test condition, or 40 cells total. Both the Teflon and Kapton cells were allowed to stabilize for over a month after lamination to eliminate the grosser post lamination adjustment effects. The gas trains were then loaded and operated for 81 days, the specimens being removed for measurement at approximately logrithmically increasing intervals. At the end of the 81 day test period, the cells were placed on ambient shelf storage. The output parameters were measured 30 days after the test was terminated, and again 80 days after termination, the latter corresponding to the end of the current reporting period.

The degradation of cells as compared to initial output parameters after 81 days exposure in the controlled environment gas trains is summarized in Table Table XLII. These results are reported to the nearest whole number percent, blanks indicating less than 1%. Each entry represents the average of 3 cells for the case ¨Kapton covered cells and the average of two cells for the FEP flash bonded cells. The upper rectangle shows the results of Kapton cells while the lower one refers to FEP cells. Both rectangles are broken down into 8 separate areas, each of which represents one of the eight test conditions. All of the cells exposed to low humidity conditions showed little change and were comparable to the standard dry shelf results.

The cells stored under the wet conditions, 95 to 100% relative humidity, were quite another matter. These cells displayed a rapid rate of degradation early in the test which tended to level out to a slower rate later. Figures 18 through 25 show the electrical parameters versus time observed in the high
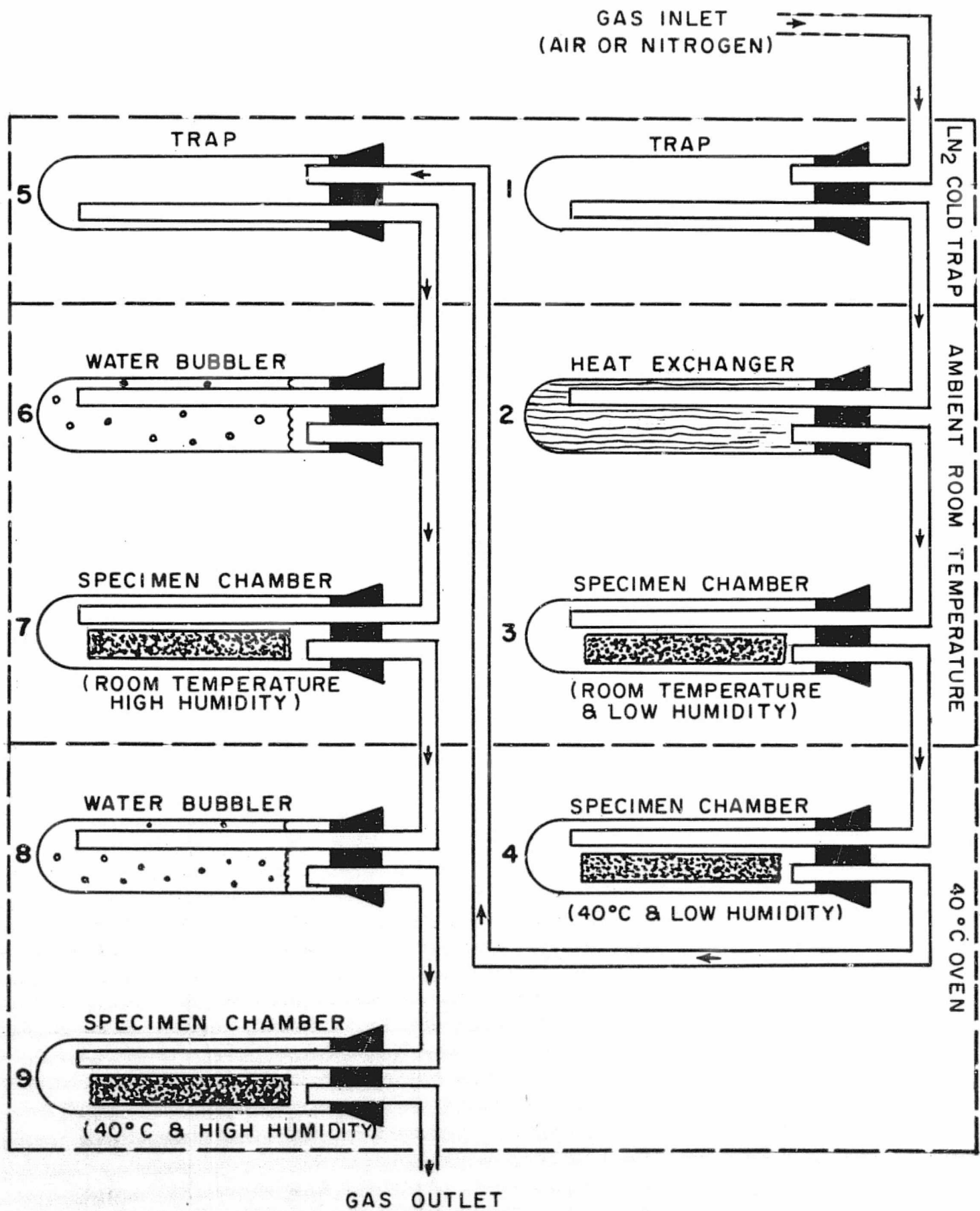
70

FIG. 17: CONTROLLED ENVIRONMENT EXPOSURE GAS TRAIN.

ERD 8235

Table XLII.   Degradation vs. Exposure Environment at 81 Days.

Kapton Covered Cells

Low Humidity (top), High Humidity (bottom); Room Temperature (left) ←→ 40°C (right). Outer corners: Air; inner corners: N_2.

	Air / Room Temp	N_2	N_2 / 40°C	Air
Low Humidity				
OCV	–	+ 1%	–	–
SCC	+ 2%	+ 3%	+ 3%	–
Max-Power	+ 2%	+ 3%	+ 3%	+ 1%
Fill	–	–	–	+ 1%
High Humidity				
OCV	– 8%	–25%	–30%	– 7%
SCC	–19%	–65%	–74%	–38%
Max-Power	–64%	–85%	–94%	–49%
Fill	–40%	–53%	–72%	–17%

Room Temperature ←——— | ———→ 40°C

FEP Flash Bonded Cells

Low Humidity (top), High Humidity (bottom). Outer corners: Air; inner corners: N_2.

	Air / Room Temp	N_2	N_2 / 40°C	Air
Low Humidity				
OCV	+ 1%	–	– 1%	+ 2%
SCC	– 4%	– 2%	– 1%	– 5%
Max-Power	– 6%	– 6%	– 8%	– 5%
Fill	– 3%	– 6%	– 8%	– 2%
High Humidity				
OCV	–54%	– 3%	– 1%	–73%
SCC	–63%	– 6%	– 8%	–91%
Max-Power	–93%	–15%	–23%	–99%
Fill	–59%	– 6%	–12%	–51%

FIG. 18: OCV vs. TIME, CONTROLLED ENVIRONMENT EXPOSURE, STANDARD PROCESS KAPTON CELLS.

73

FIG. 19: SHORT CIRCUIT CURRENT vs. TIME, CONTROLLED ENVIRONMENT STORAGE, STANDARD PROCESS KAPTON CELLS.

ERD 8237

74
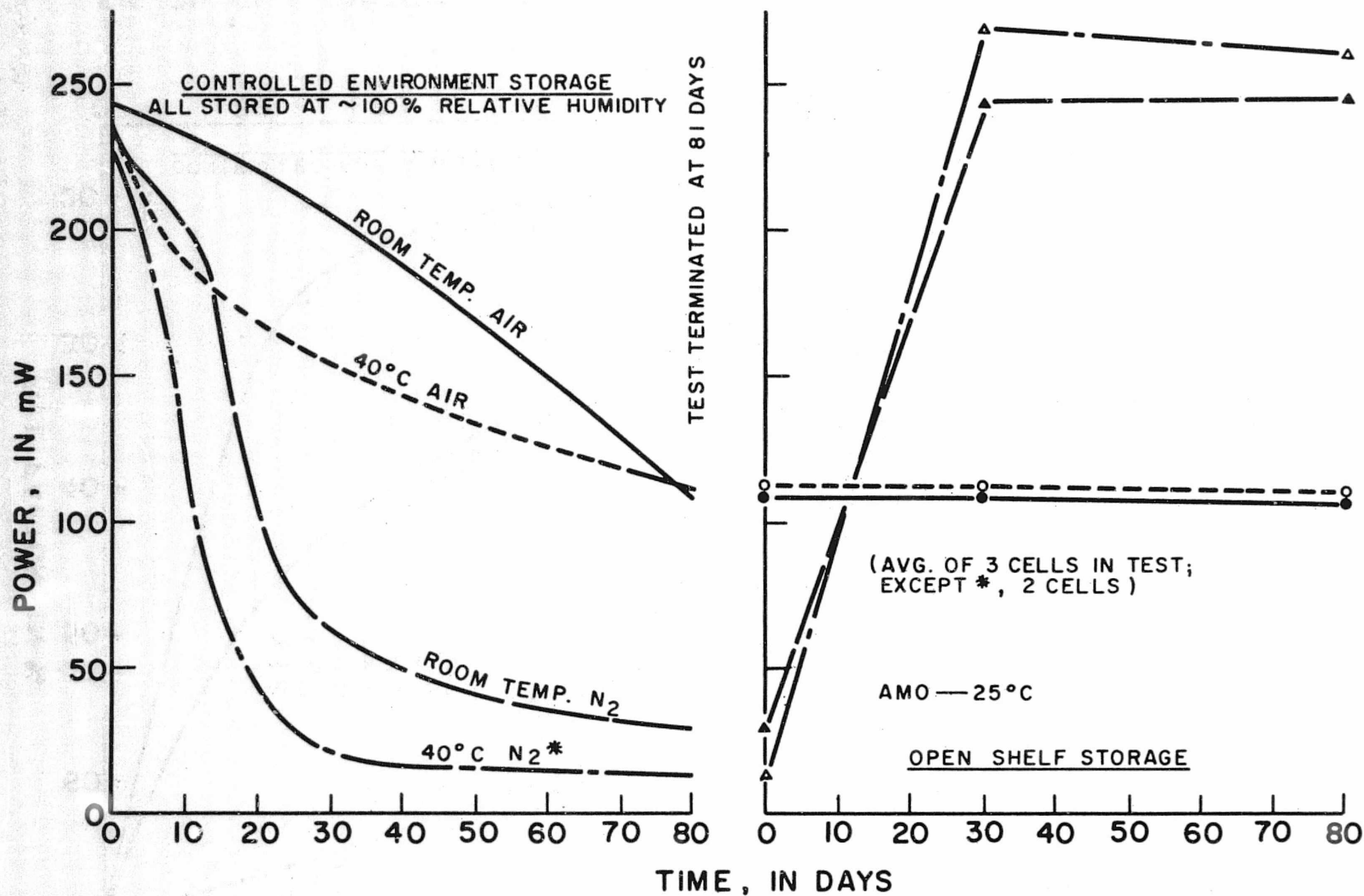
FIG. 20: MAXIMUM POWER vs. TIME, CONTROLLED ENVIRONMENT EXPOSURE, STANDARD PROCESS KAPTON CELLS.
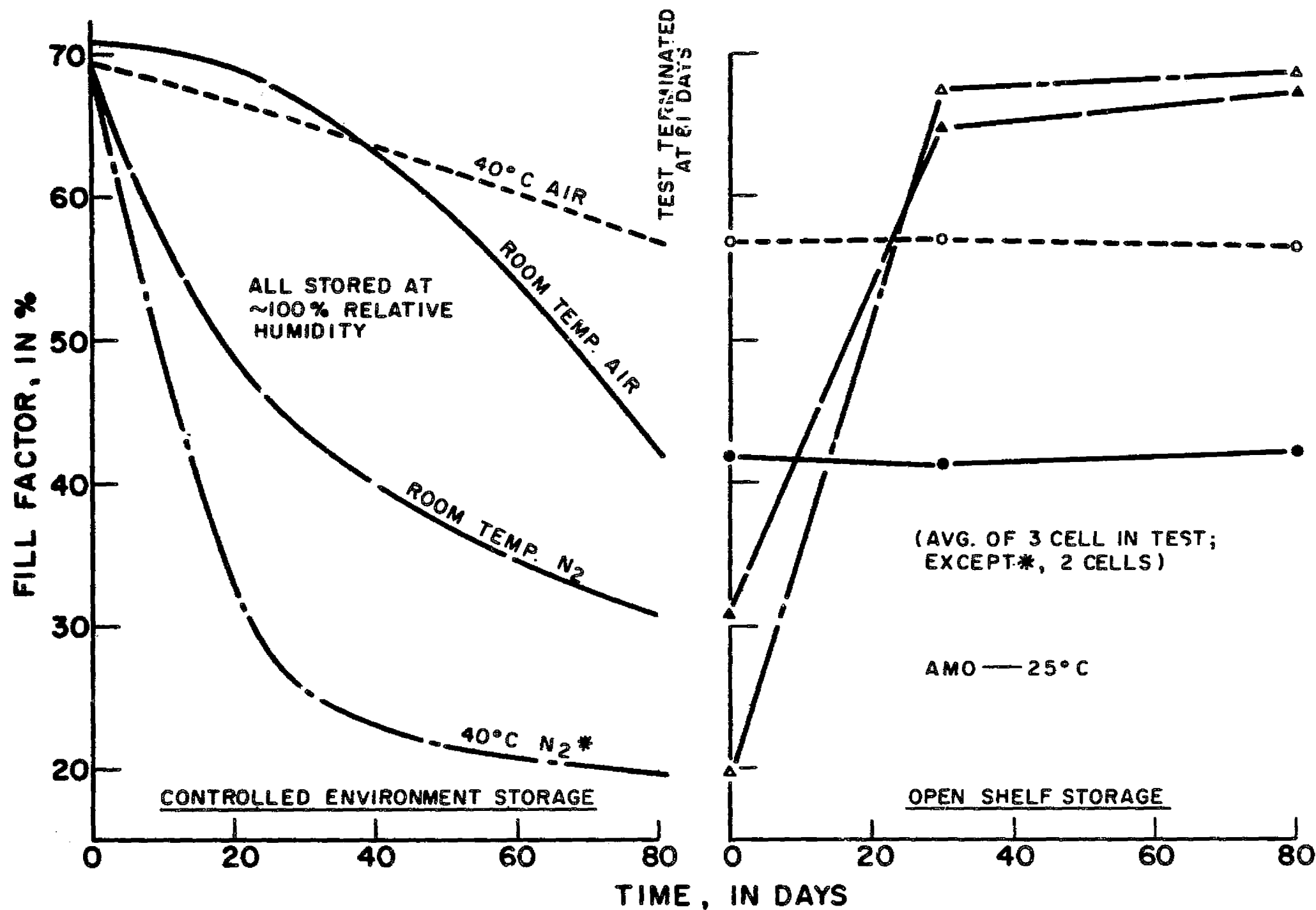
FIG. 21: FILL FACTOR vs. TIME, CONTROLLED ENVIRONMENT STORAGE, STANDARD PROCESS KAPTON CELLS.
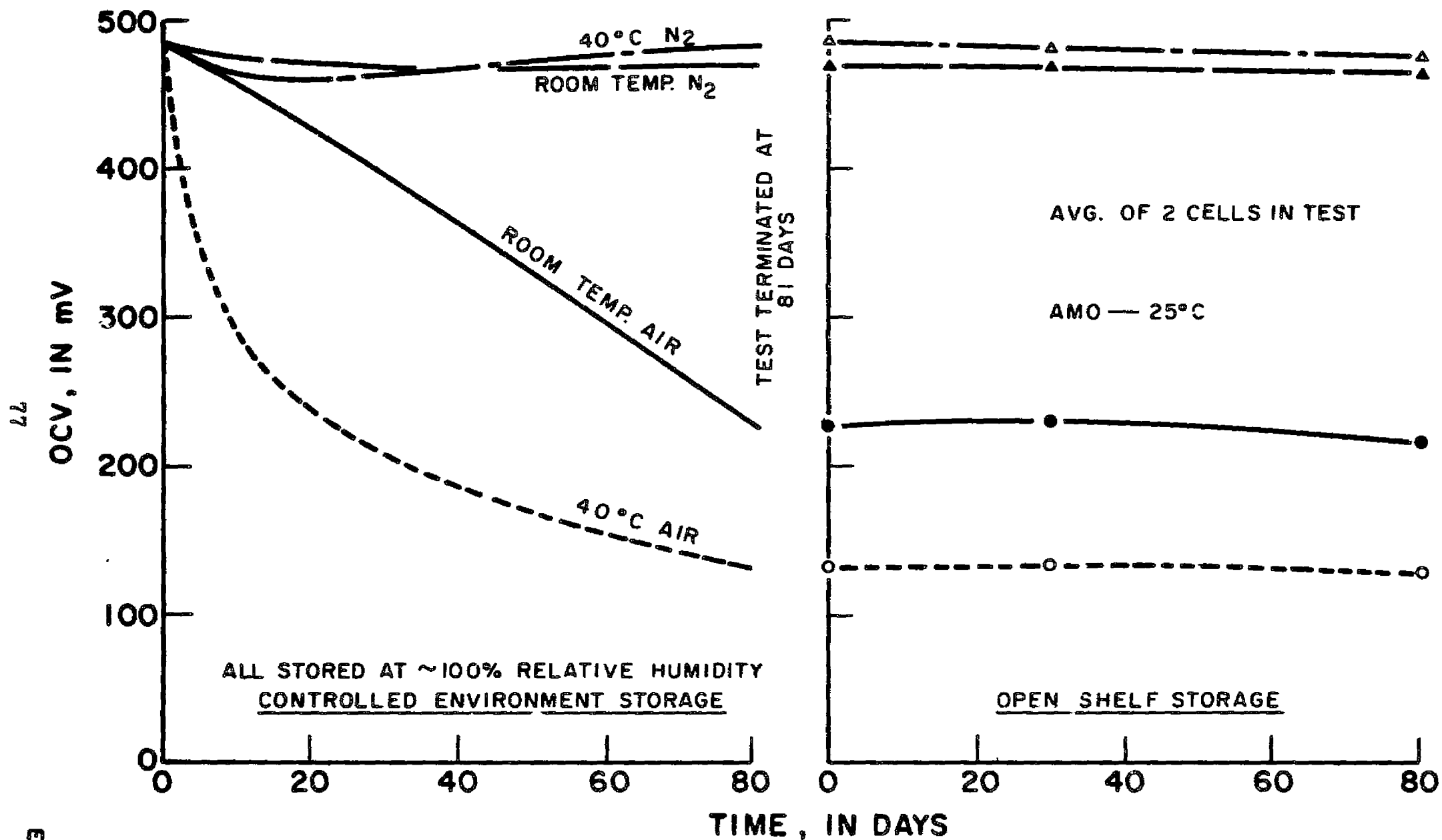
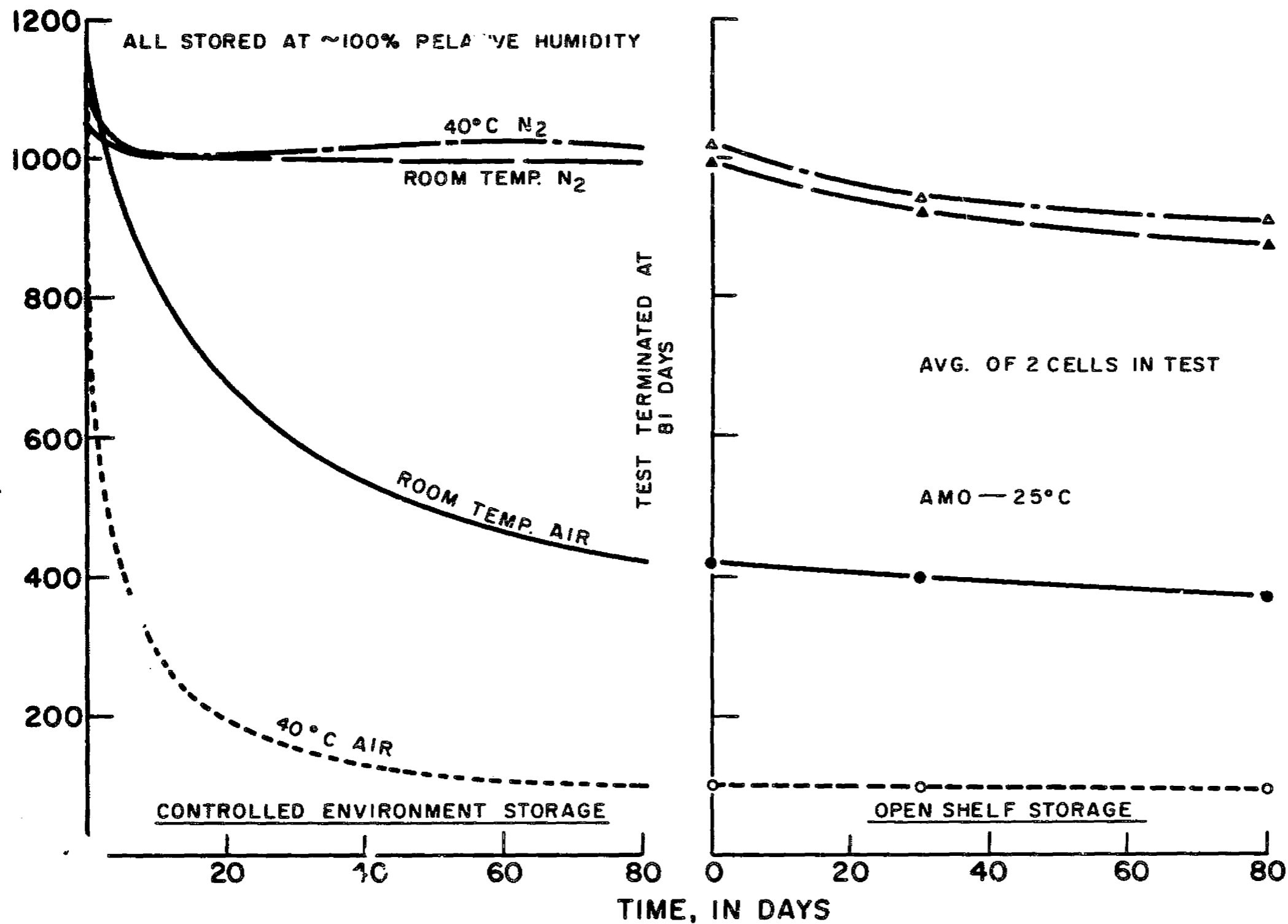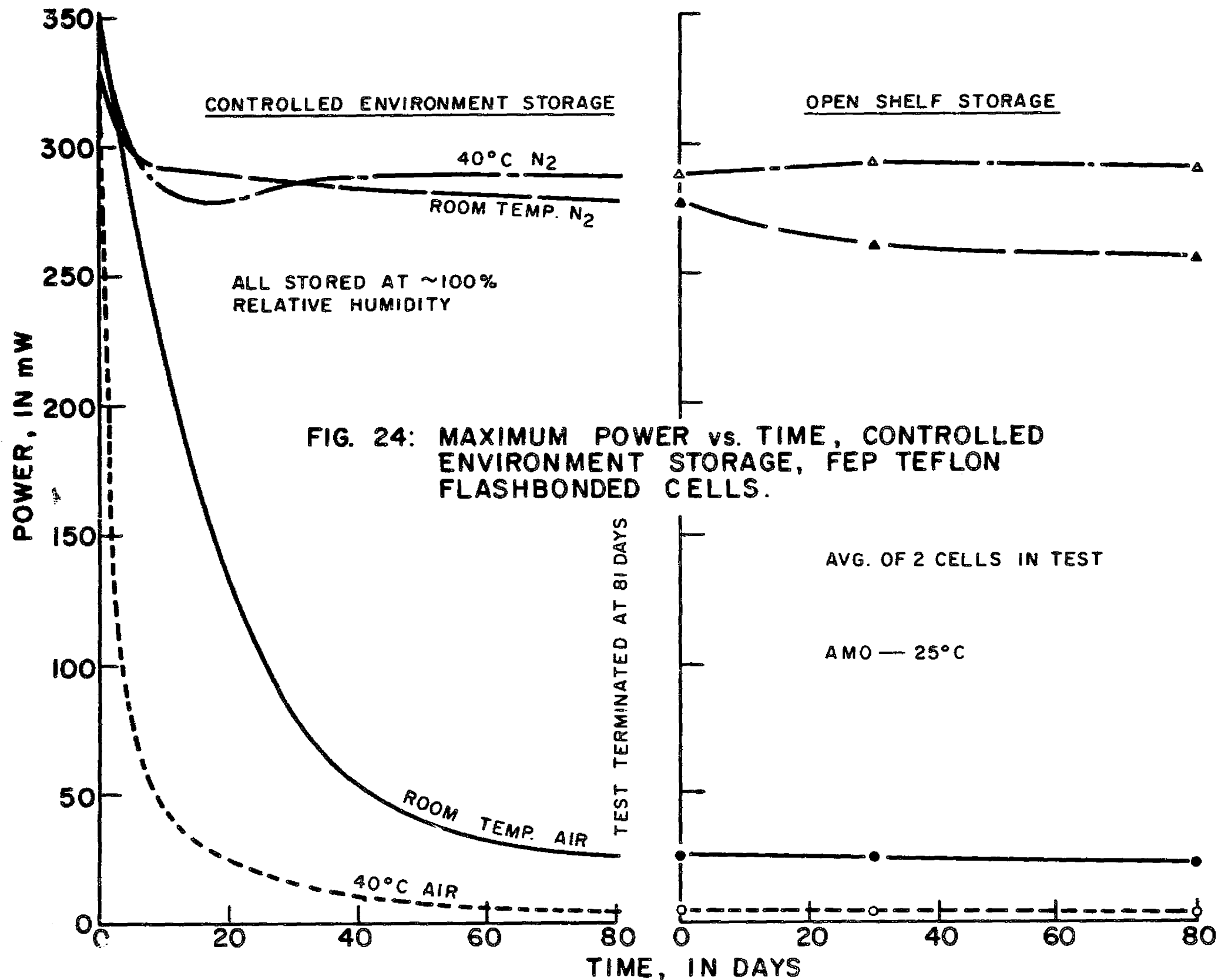FIG. 22: OCV vs. TIME, CONTROLLED ENVIRONMENT EXPOSURE, FEP TEFLON FLASHBONDED CELLS.

FIG. 23: SHORT CIRCUIT CURRENT vs. TIME, CONTROLLED ENVIRONMENT STORAGE, FEP TEFLON FLASHBONDED CELLS.

ERD 8241

78

FIG. 24: MAXIMUM POWER vs. TIME, CONTROLLED ENVIRONMENT STORAGE, FEP TEFLON FLASHBONDED CELLS.
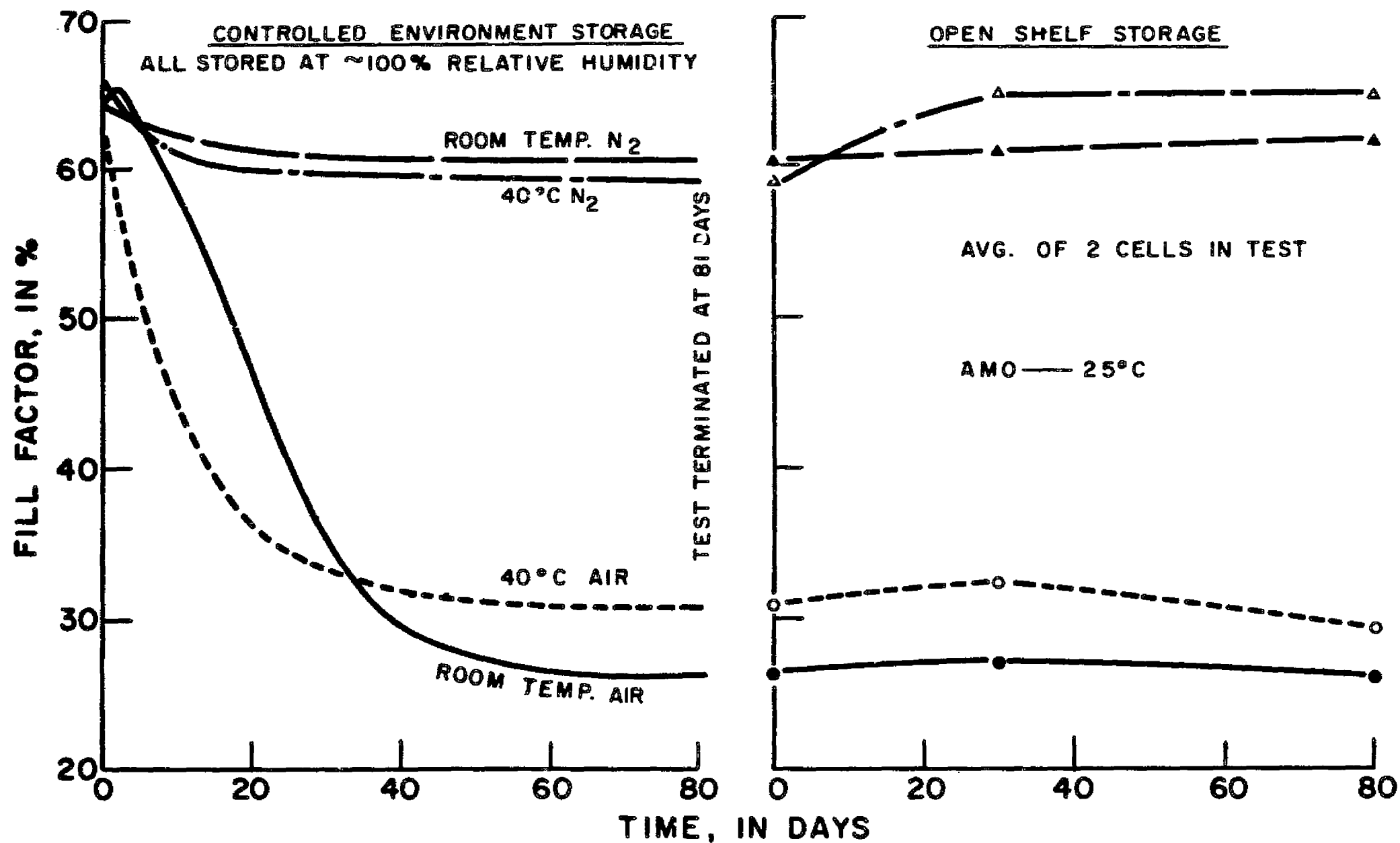
FIG. 25: FILL FACTOR vs. TIME, CONTROLLED ENVIRONMENT STORAGE, FEP TEFLON FLASHBONDED CELLS

humidity test, as well as the two measurements made at intervals after the test was terminated. The first peculiarity noted upon comparing these curves was that the flash bonded Teflon cells showed a rapid and maximum degradation during exposure to air both at room temperature and at 40°C at the high humidity level. But most unexpected was that the Kapton cells showed maximum sensitivity to high humidity in nitrogen.

These results are obviously in contrast to the 80% relative humidity storage data discussed earlier. The magnitude of the degradation shown in Table XLII in 81 days is much greater than the degradation seen on any cell on the 80% relative humidity tests in the same time period. This implies that increasing the relative humidity from 80% to nominally 100% has a precipitous effect on the moisture stability of the thin film cell. These results are corroborated by similar results of other recent tests of wrap-around Kapton covered cells exposed to 100% relative humidity at 38°C. Significant degradation occurred within a week on all cells so exposed. This contrast between the results in air and in nitrogen is even more puzzling when it is considered that the natural air used doubtlessly contained the usual 78% atmospheric nitrogen! The presence of normal atmospheric oxygen apparently has just the opposite effects on the two types of cells, the FEP cells degraded more in moist air than in the moist nitrogen, while the Kapton cells appeared to degrade more in moist nitrogen than in moist air. The effect however was more pronounced in the FEP cells. Furthermore, the measurements taken 30 days and 80 days after the test was terminated revealed that the degradation was permanent on the degraded FEP cells while the badly degraded Kapton cells showed full recovery.

Analysis of these results, if the cells are assumed to be identical except for dissimilar cover plastics, appears to be hopeless. The dissimilarity between the two cover plastics is in reality too small to account for the gross differences. Mr. L. R. Shiozawa of Gould Labs has calculated that sufficient oxygen can pass through the 1 mil Kapton under one atmosphere pressure at 20°C to completely convert the copper in the barrier as copper oxide in less than 24 hours, if the rate of the chemical reaction were high enough to utilize the oxygen as rapidly as it became available. And since FEP Teflon is even more transparent to oxygen than Kapton, the rate of oxidation in either case is evidently not limited by any unavailability of oxygen.

On the other hand, if the crystal structure of the Cu_2S barrier layer were assumed to be different in the flash bonded Teflon cells than in the Kapton cells, a situation believed to be realizable on the basis of the different temperature histories of cells during their fabrication, then a plausible explanation becomes available. Let us assume that the Cu-S phase present in the case of flash bonding temperature history is more reactive with oxygen than in the case of the epoxy bonding temperature history. This simultaneously satisfies the observation as seen in Table XLII, that the flash bonded Teflon cells show more degradation upon exposure to air than the Kapton cells, regardless of temperature and humidity conditions. Then calling to mind that the preponderance of experimental data indicates that some oxygen exposure during barrier formation appears necessary for normal operation of the cell, it becomes conceivable that the partial pressure of oxygen in the nitrogen side of the gas train could be low enough to cause some of the empirically necessary oxygen to be removed from the normal

barrier layers, but not from the barriers subjected to the flash bonding temperature history containing the phase having (hypothetically) increased oxygen affinity. This would account for the extreme degradation of the Kapton covered cells in contrast to the mild degradation of the flash bonded Teflon cells exposed to nitrogen at high humidity. The remaining inconsistency to be rectified is the Kapton cell's lack of degradation in dry nitrogen. This requires that the water vapor reaching the barrier participated either catalytically or electrolytically in the de-oxygenation process, the effect still being ultimately caused by the absence of oxygen. It is unfortunate that the CuS phases in the cell arising from different temperature histories have not been identified and that the free energy of formation, hence the oxygen reactively, of the several candidate phases that exist in the neighborhood of $Cu_{2.00}S$ stoichiometry are not yet available from the literature. Without these data, it will be difficult to corroborate this hypothetical explanation of the results of the controlled environment exposure experiment.

One result of this experiment, however, is useful on an entirely empirical basis. Prolonged storage of the cells before actual use can be accomplished with minimum degradation by the simple expedient of employing desiccated storage facilities.

Other Experimental Cover Plastics. - In addition to the work done with FEP Teflon, considered to be the most promising of the alternate cover plastics, several other materials were evaluated. These included several weatherable polyesters, Aclar and a multilaminar TFE-FEP Teflon. The use of FEP Teflon as an alternate adhesive system to the standard process Astroepoxy was evaluated.

The weatherable grades of polyester films became available for evaluation late in the reporting period, and consequently received only cursory evaluation. Materials received for evaluation included Scotchpar X54270 weatherable polyester and two gauges of weatherable Mylar from Martin Processing Company. These materials achieve their ultraviolet resistance from a filler which is highly absorbent in the UV range. Several cells were fabricated using the Scotchpar material. These cells were indistinguishable from ordinary Mylar covered cells in appearance and performance. No cells were completed using the Martin Mylar. The optical transmission spectra of these polyesters are shown in Fig. 26.

Aclar*, a chlorotrifluoroethylene similar in structure to TFE Teflon, was examined with renewed interest when the pure polymer, Aclar 33C, became available. The copolymer material, Aclar 22A,[5] had been shown to degrade rapidly, exhibiting brittle-failure, under exposure to UV or particle radiation in tests conducted at NASA-Lewis Research[6] disqualifying it from consideration as a cover plastic material-of-choice. In the event that the 33C Aclar proves to be more resistant to this radiation damage, because of its superior gas/vapor impermeability, optical clarity and adequate temperature resistance, it would satisfy the qualification requirements to become an improved alternative cover plastic to the Kapton film now in use. Additionally, the 33C Aclar was found to be heat sealable by the flash bonding technique developed for FEP Teflon, the only modification required being the use of Allied Chemical Corporation's

*Trade Mark of Allied Chemical Corp.

KH-1 primer on the bonding surface and a lower flash bonding temperature, 230°C to 260°C producing satisfactory bonds.

As an alternative to the use of FEP Teflon as the top cover plastic because of FEP's poor results when exposed to high humidity, low resistance to mechanical abrasion and the occasional problem of grid wires punching through the cover during flash bonding, a multilaminar FEP-TFE Teflon film produced by Dilectrix Corporation was evaluated. Attempts to flash bond this film directly were frustrated by the insufficient thickness of the FEP layer, resulting in extensive voiding due to inadequate plastic flow into the grid openings. This problem was solved by using an additional 1 mil FEP film between the gridded barrier and the FEP face of the multilaminar film. However, a spot check showed no improvement in the moisture resistance of cells made with this cover material despite the alleviation of the mechanical abrasion and grid punch through problem.

The use of the FEP Teflon as an adhesive for attachment of an additional plastic layer was extended to the application of a Kapton cover by flash bonding, eliminating the use of transparent cover-epoxy altogether. The several flash bonded Kapton cells produced by this technique were indistinguishable from their epoxied counterparts both in appearance and initial performance. Time did not permit extended tests of these cells.

The optical transmission spectra of the alternate cover plastics investigated were measured in the useful bandwidth of the CdS cell. The transmission spectra of the weatherable polyesters, the halocarbons, and several thicknesses of Kapton films are shown in Figs. 26, 27, and 28, respectively. The dropping characteristic towaid shorter wavelengths observed in the halocarbon materials is believed to be due to scattering, a pronounced haze being apparent in the multilaminar film and a slight haze being visible in the Aclar and FEP viewed in strong illumination. Initial output parameters of cells covered with these materials indicated that the scattering had negligible effect on cell efficiency. The protection afforded the cover epoxy against UV by Kapton film is evident in Fig. 28 , as well as the costly reduction of efficiency assignable to rejection of the useful energy between 0.40 µ and 0.55 µ . In the event that the weatherable polyesters in Fig. 26 prove durable in the space environment, they offer an attractive alternative to Kapton, providing an UV barrier to protect the epoxy at a much reduced efficiency penalty.

Peel Tests. - Peel tests were initiated in order to compare the strengths of the various experimental FEP cover plastic and bonds with one another and with the Kapton-epoxy bond used in standard process cells. The test was designed around ASTM Standard D903-49. Cells were fabricated for the test by leaving their cover plastics unattached for about 3/8 inch along the negative tab and then cut into strips 5/16 inch wide. Clamps were attached to the loose cover plastic and to the negative tab. A spring type force gauge was used to measure the pull forces.

Rather surprisingly, in no instance among all the samples tested, both experimental and standard process, was the cover plastic bond weak enough to allow its measurement. Separation always occurred elsewhere in the cell before
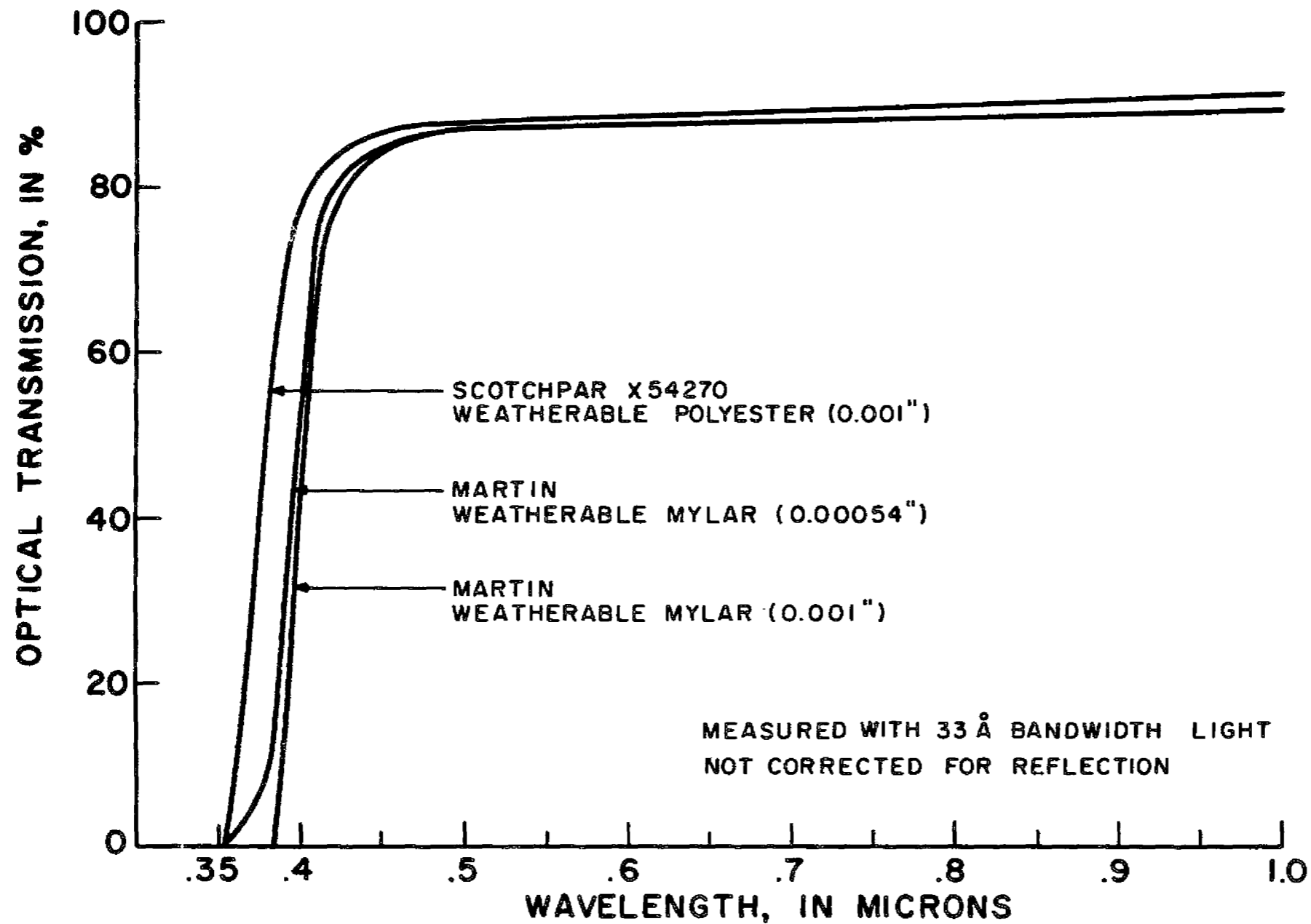
FIG. 26: OPTICAL TRANSMISSION vs. WAVELENGTH
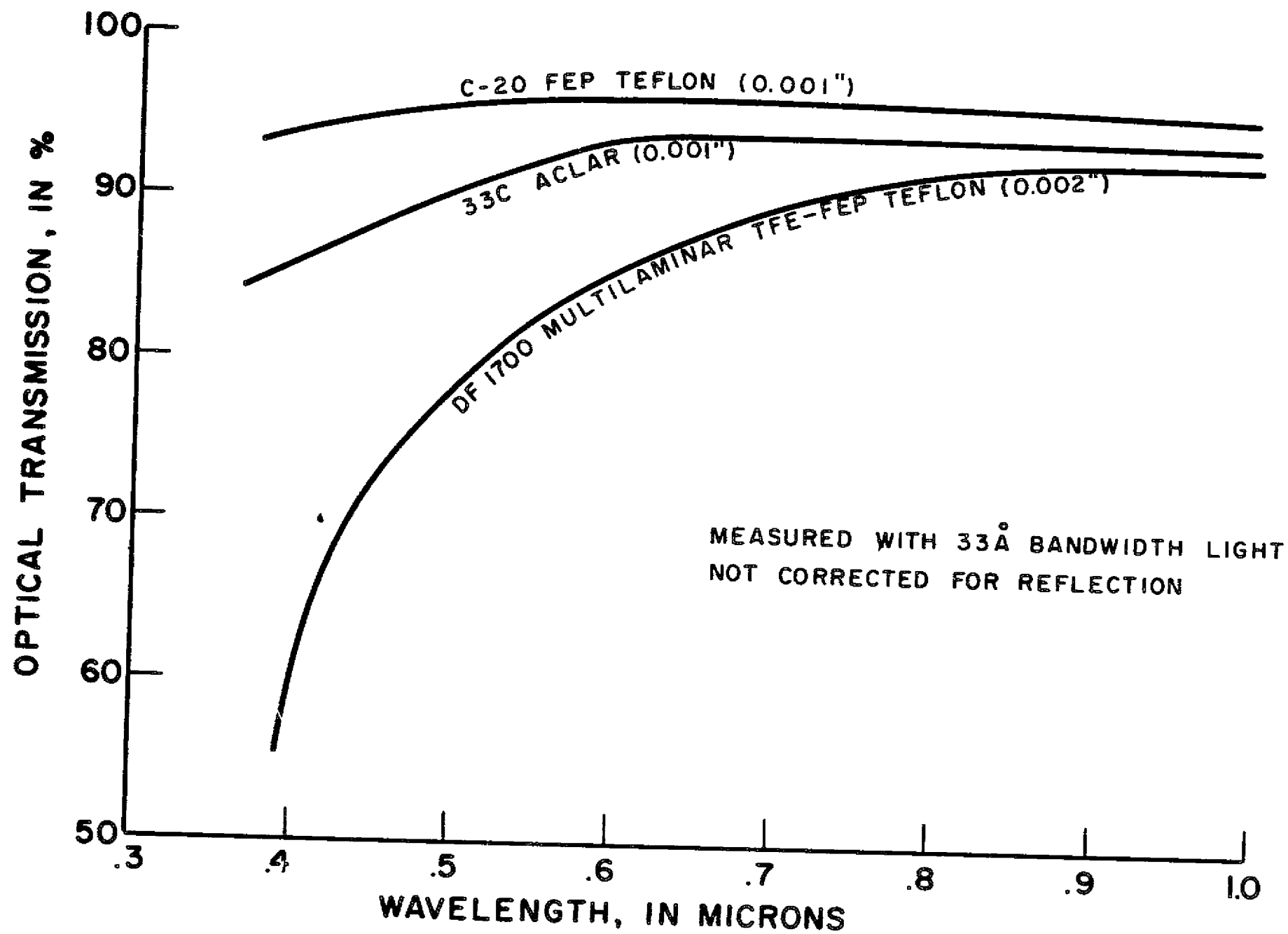**WEATHERABLE POLYESTERS**

FIG. 27: OPTICAL TRANSMISSION vs. WAVELENGTH
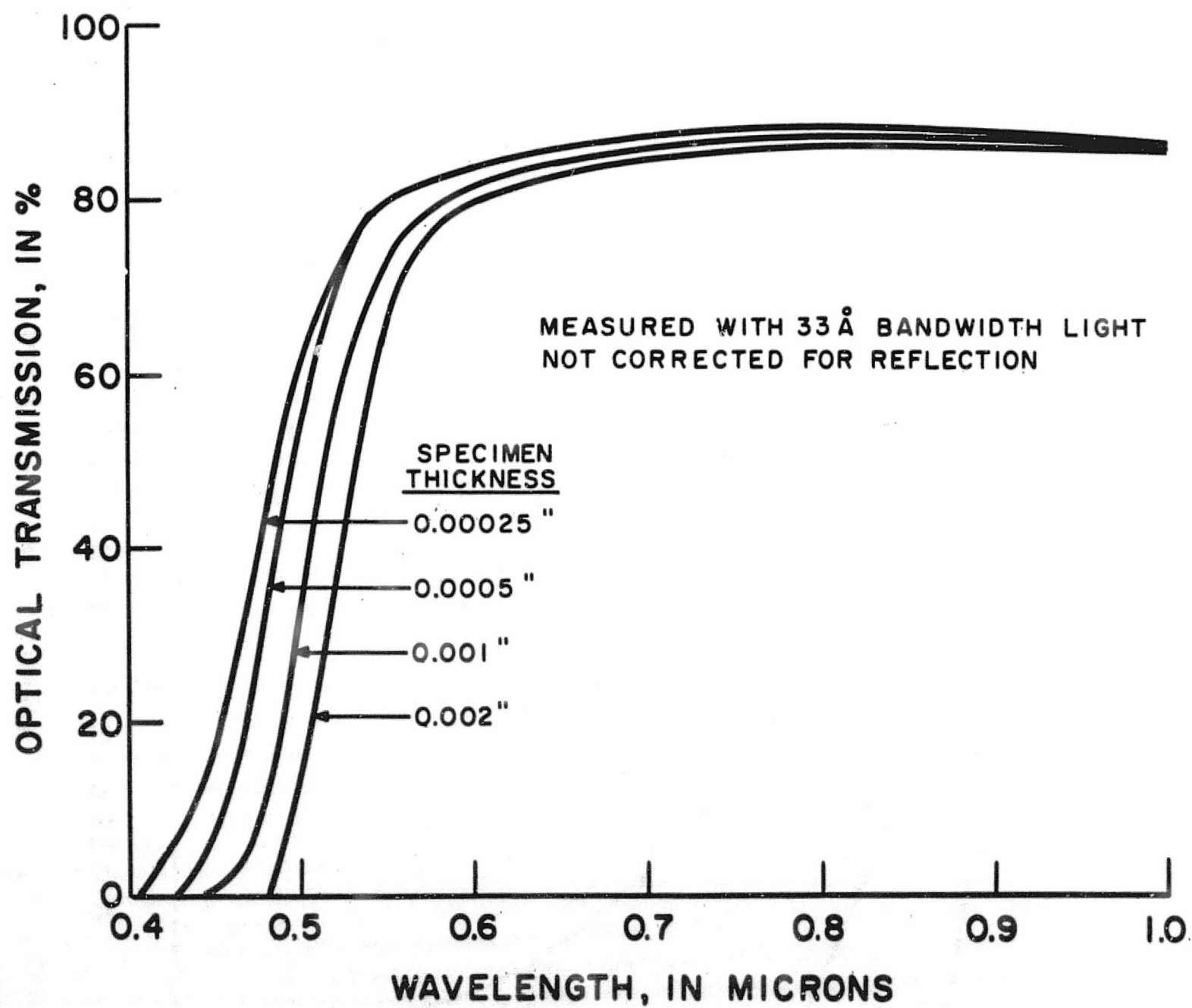TEFLONS AND ACLAR

FIG. 28: OPTICAL TRANSMISSION vs. WAVELENGTH
KAPTON FILM

it occurred at the cover plastic bond, usually at the Kapton-Ag Pyre ML interface, the Ag Pyre ML-CdS interface or in the CdS film itself. In addition, the FEP experimental covers tore quite frequently, but separation at the interface between the cover and the gridded barrier layer was never observed.

These results confirm what has been suspected for some time, that the cover plastic bond, at least immediately after cell fabrication, is generally stronger than most of the other interfaces in the cell.

Thermal Shock Tests. - The ability of experimental as well as standard process cover plastic-adhesive combinations to withstand thermal shock tests was determined in a related task. Cells were cycled by immersion in liquid nitrogen for one minute followed by withdrawal into a 60°C argon stream for another minute. Six cells could be tested at a time and 600 cycles were selected for the test duration. A thermocouple was cycled along with the cells to indicate the actual resulting temperatures.

The first group of cells cycled contained two standard process Class I Kapton covered cells, and four cells with FEP covers, three of which were attached with adhesives, Epotek 301*, Uralane 8666* amd Epoxy #30*. The fourth was heat bonded.

As in the case of the peel tests no cover plastic delamination occurred on any of the six cells, only separation at the other interfaces. Separation in the CdS layer was most frequent among these cells. After 10 cycles the cells with Epotek 301 and Epoxy #30 showed much separation along both edges while the two Class I cells showed separation along one edge. After 70 cycles the Epotek and Epoxy 30 cells showed such large separation areas that they were removed from the test. The remaining four were kept on through 600 cycles. Again, none of the cells showed cover plastic delamination, but separation was common at the CdS layer or some other interface.

The cells were removed from the test after the following number of cycles for testing and inspection: 10, 30, 70, 150, 230, 310, 390, 470, 550 and 600. Mechanically all the cells tested apparently passed the test, in that none of their cover plastics delaminated. However, there was much variation in their electrical performance. All cells suffered some degradation, most of which was in loss of SCC, which was expected due to the loss area caused by the separation at the substrate or in the CdS layer. OCV and fill were only slightly affected while the loss in efficiency was comparable to the loss in SCC. Data are shown in Table XLIII.

*Epotek 301, Trade Mark of Epoxy Technology Inc.
*Uralane 8666, Trade Mark of Furane Plastics.
*Epoxy #30, Trade Mark of Transene.

Table XLIII.   Actual and Relative Performance After 600 Cycles
of Thermal Shock Testing

Cell Number	Cover	OCV	SCC	Fill	Eff.
54-356	Kapton	460/99	680/91	69.7/101	2.84/92
54-357	Kapton	466/98	585.86	69.5/99	2.47/84
269-352	FEP Heat Bonded	420/98	850/74	33.7/91	1.57/66
266-354	FEP Epoxy 30	459/100	1050/88	64.3/99	4.04/87
266-351	FEP Epotek 301	465/100	1020/85	67.5/101	4.18/86
269-353	FEP Uralane 8666	448/98	920/85	60.5/95	3.20/80

Two additional groups of cells were subjected to the 600 cycle test after the flash bonding technique had been developed   The second group consisted of 3 FEP flash bonded cells and 3 Kapton cells with wrap-around covers as control specimens.   The third group consisted of 2 barriered films, 2 FEP flash bonded cells with wrap-around covers and 2 FEP flash bonded cells with edges protected by a "V" fold of pressure sensitive tape.

The wrap-around Kapton cells completed the 600 cycles of testing unscathed; all parameters remained within the error of measurement at all times.   The non-wrap-around FEP flash bonded cells showed immediate and progressive failure by the previously observed mode of splitting in the CdS layer.   The splitting initially appeared along the cell edges and propagated inwardly.   The SCC and maximum power approximately followed the reduction in area due to separation in the CdS layer, but the OCV and fill remained essentially constant.

The wrap-around flash bonded cells did not show separation along the wrapped cell edges.   But a decrease in SCC led to the discovery during the 470th cycle intermission that splitting in the CdS layer along the cut edge behind the positive tab on one of the cells was occurring.   Failure of cells due to splitting in the CdS layer is believed to be characteristic of cells tested individually and would be unlikely to occur in arrays of cells bonded between array cover plastic sheets.   Splitting in the CdS layer is assumed to be caused by the counter strains of the front and back plastic films on the CdS layer due to the mismatch in thermal expansion coefficients of the plastic and the CdS.   By making the top and bottom plastics continuous, as in the wrap-around edge, the strains on the CdS layer are considerably reduced.

The only change observed in the barriered CdS films through 600 cycles of testing was a slight crazing in the portion of the unbarriered CdS film extending onto the negative tab and extending beyond the zinc interlayer.   Splitting in the CdS film was not observed, and was not expected since the sandwich construction was not present to set up the counter strains in the CdS layer.

The flash bonded cells, whose edges were protected by a "V" fold of Kapton tape, degraded rapidly after the first 10 cycles.   In addition to the "V" fold strip not providing the degree of protection anticipated, the situation was

aggravated by the fact that the additional width of the "V" fold strip could not be accommodated by the cell holder and resulted in crumpling the cells during installation. Consequently the cells buckled apart through the CdS layer, which effectively reduced the active area of the cell. This failure mode is believed to be completely artifactual and due to the poor fit of the cell in the holder.

Figures 29 and 30 summarize the SCC and efficiency behavior versus completed temperature cycles for the FEP cells tested.

GRID OPTIMIZATION

One of the specified tasks of the program was to determine if the geometry of the presently used 60 line per inch grid was optimized for the existing cell. Many changes have been incorporated into the cell since the present design grid was selected so an optimization procedure was felt warranted. The existing grid can be visualized as serving a dual purpose: first, as a collector of the current generated within the cell; and second, as a carrier of that collected current to the positive tab. These two functions can be isolated quite easily to determine how variations in their parameters affect cell performance.

The effect of varying the grid resistance was studied by progressively severing the closely spaced grid lines from the positive tab of a group of gridded cells that had no attached cover plastics. Every other grid wire was carefully cut at the positive tab and then an I-V trace was taken to determine the effect of this 50% reduction in current carrying capacity. Curves were thus obtained with the following number of wires still intact: 168 + bus bars (initial), 168, 84, 42, 21, 11, 6, 3, 2 and 1.

Surprisingly, no significant effect was observed until only 22 of the original 168 wires, or 13%, remained. The resistance of a single grid wire between the positive tab and the first cross wire was calculated to be 0.041 ohms. Thus when 22 grid wires remained uncut, the series resistance between the tab and the bulk of the remaining grid was only about .0018 ohms. Variations in series resistance of this small magnitude are undoubtedly too small to be detected in the I-V traces. Figure 31 shows how the I-V traces deteriorated as the number of intact wires was reduced from eleven to zero. It is significant that with only one line remaining a fairly normal I-V trace was still obtainable.

These studies would indicate that the current carrying capability of the presently used grid is more than adequate and, if necessary, could probably withstand a substantial increase in its resistance.

In order to determine if the line density of the present grid were still adequate, it was felt that the most definitive results could be obtained by actually fabricating cells with differing line densities. The results of this study were anticipated to be of use in solving the series resistance problem which was then plaguing the standard process fabrication line. The barrier layer was suspected of having increased its resistance and simply by varying the grid line density it could be determined if the barrier layer was a significant contributor to the total series resistance.
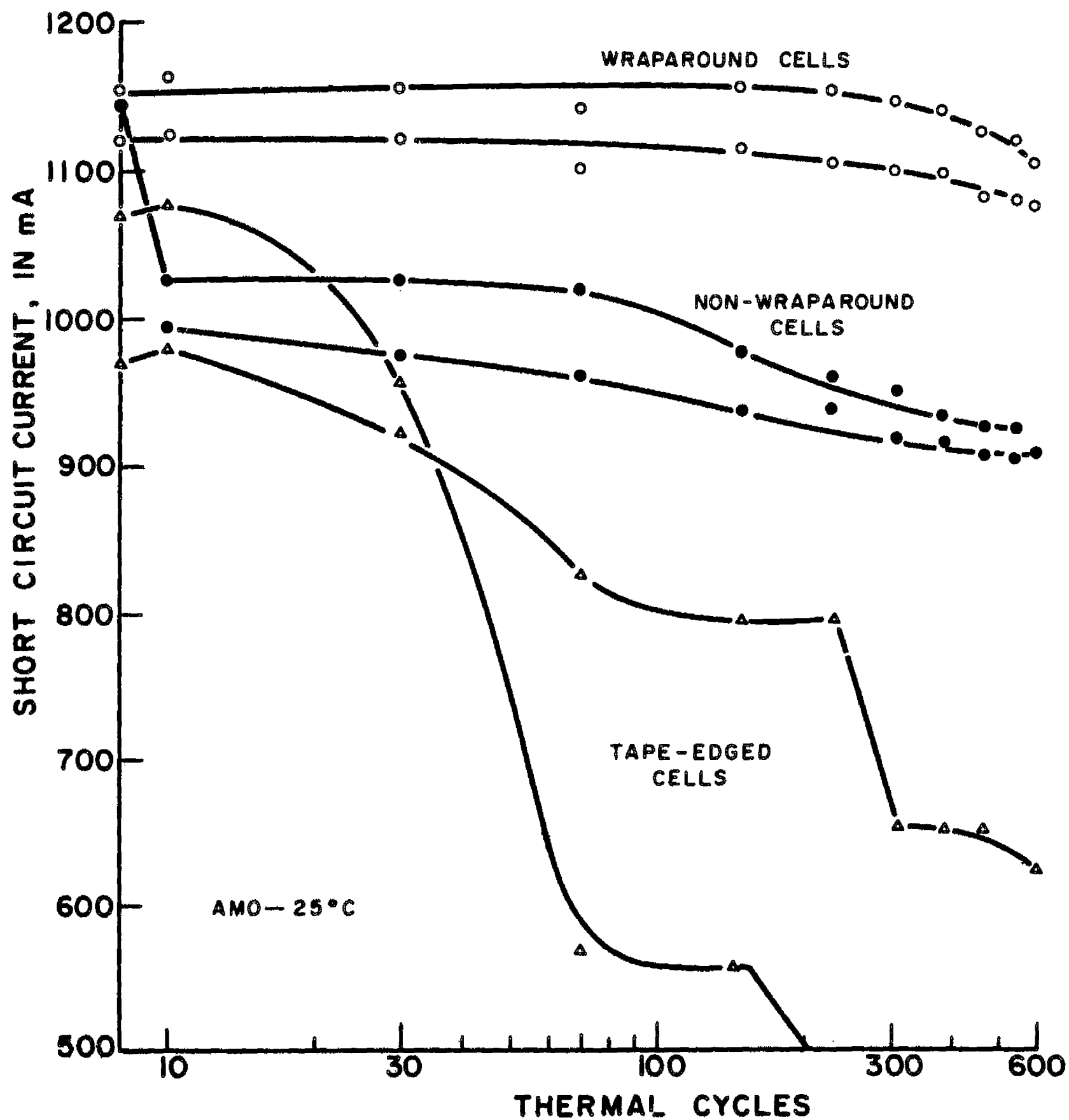
89

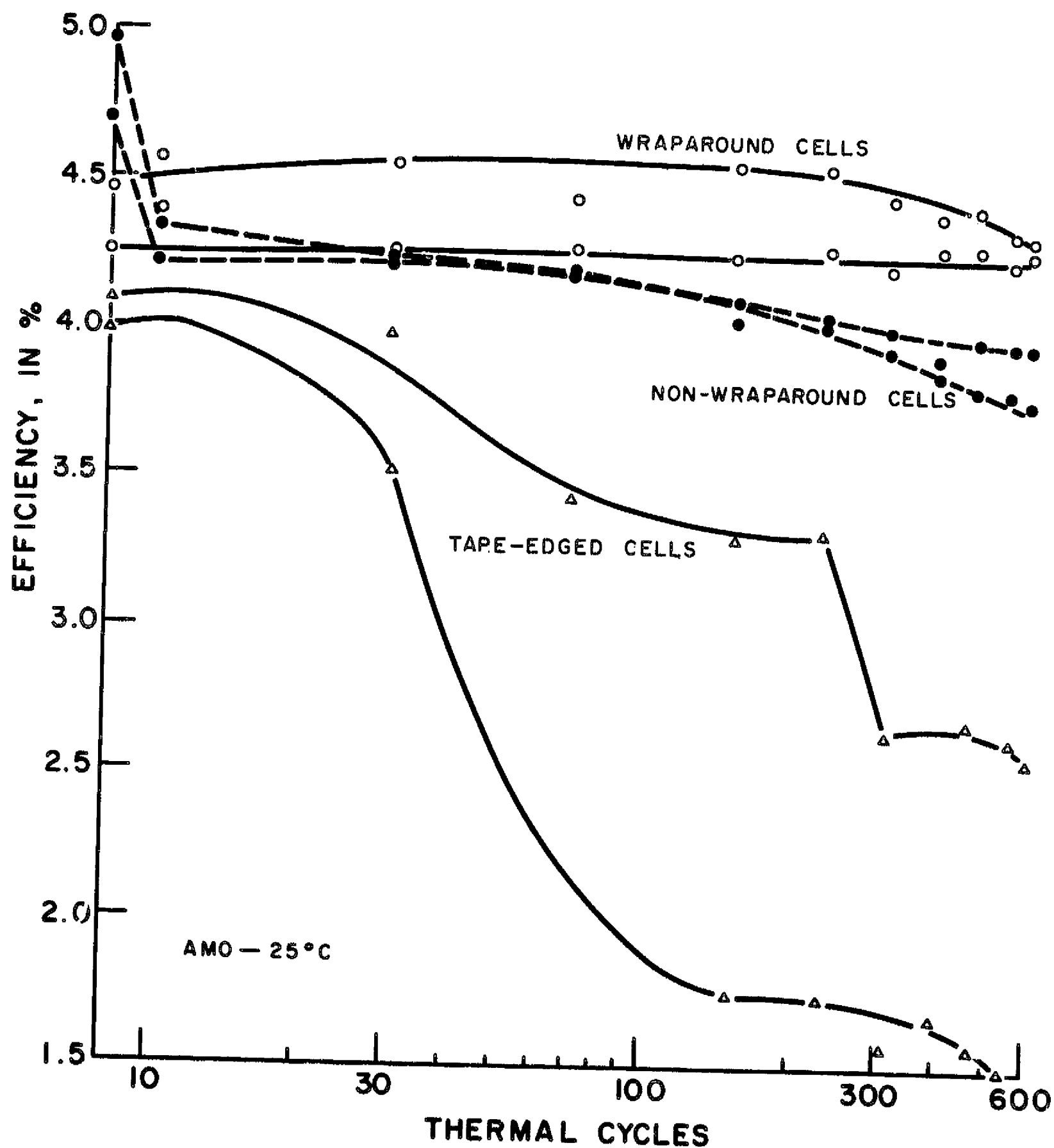FIG. 29: SCC vs. THERMAL CYCLES. FEP FLASHBONDED CELLS.

90

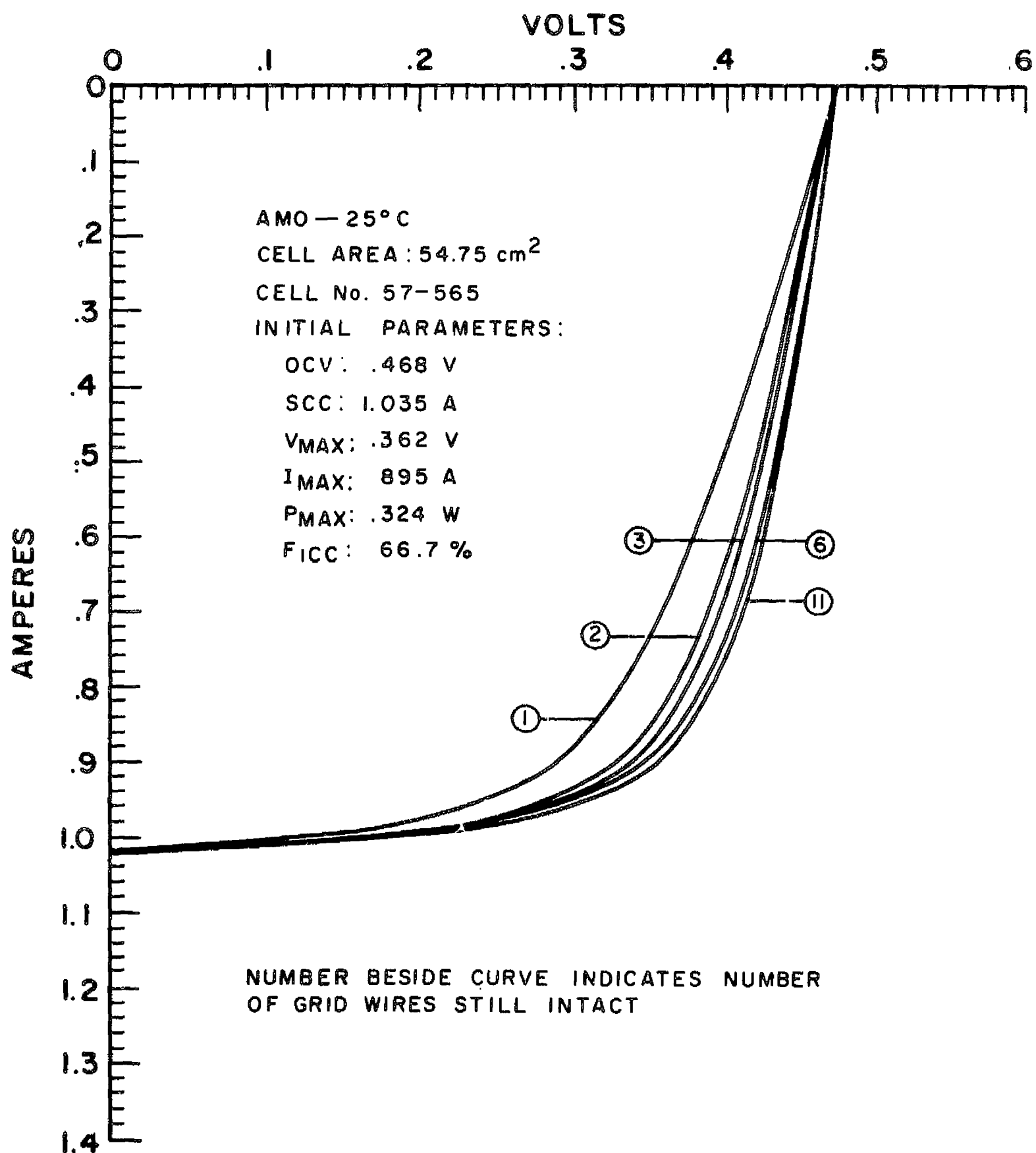FIG. 30: EFFICIENCY vs THERMAL CYCLES. FEP FLASHBONDED CELLS.

FIG. 31: I-V CURVES WITH VARIOUS GRID WIRE CUT.

Line densities of 50, 70 and 80 lines per inch, in addition to the standard 60 lpi, were selected in order to determine if any trends were present close to the existing density, which would then be more carefully defined by a second set of varying line density patterns. The time and cost of preparing the photographic master grid pattern which is subsequently used in the actual production of the photo etched grid has always been a deterrent to grid studies in the past. This problem was partially overcome by deciding to simply photographically enlarge and reduce the existing 60 lpi master in order to obtain the 50, 70, and 80 lpi masters. Thus the 50 lpi master was obtained from a 1.2X linear enlargement of the 60 lpi master and the 70 and 80 lpi masters were obtained by .857X and .750X linear reductions. This method also maintains approximately the same light transmission among the four densities, a necessary requisite for a valid comparison of the four designs. As a result the dimensions of the four patterns were all different and in order to obtain cells of a uniform size, the 50, 60 and 70 lpi grids were carefully cut down to the dimensions of the 80 lpi grid, the smallest of the four. The grids were therefore exactly 3/4 the linear dimensions of a regular grid, but the effective cell areas varied slightly from that figure because of margins. Actual effective cell area was 31.5 sq. cm.

A total of eleven substrates was used for the experiment. Two cells of each of the 4 different densities were fabricated from every 9-cell substrate, the remaining cell was rotated among the four. Other than the differing grids and dimensions the cells were fabricated according to the standard process in all other respects.

The means and the standard deviations of the significant AM0-25°C performance parameters of the four groups of cells are listed in Table XLIV The series resistance was determined, as previously mentioned, from the slope of the I-V characteristic as it crossed the voltage axes.

As has happened so consistently in the past fluctuations produced elsewhere in the cell fabrication process are as large, if not larger, than any variations that may have been experimentally produced.

If the barrier layers were making a significant contribution to the total cell series resistance then the indicated series resistance ought to decrease as the line density was increased. The distance between adjacent lines at 50 lpi is 20 mils and at 80 lpi is 12.5 mils, or a decrease of 37.5%. Hence the resistance of the barrier layer, and ultimately cell series resistance, ought to show a significant decrease as the grid line density is increased from 50 to 80 lpi. The average series resistance does show a very slight downward trend, but hardly significant.

In addition an increasing fill should also accompany a decreasing series resistance, and while a trend is present it is very non-uniform. Such a trend ought to be quite obvious among the 9 cells from each substrate since cells of each line density were fabricated from each substrate. Table XLV shows how the fills varied in 10 of the 11 substrates used. In none of the substrates did all of the cells follow the variations in grid line density, but the ones indicated showed the trend in their averages.

Table XLIV.   AM0-25°C Performance of Kapton Covered Cells with Differing Line Density Grids, 31.5 cm^2 Area

	Mean	Standard Deviation
50 lpi (23 cells)		
OCV	.473 V	.020
SCC	15.5 mA/cm^2	0.84
Pmax	4.88 mW/cm^2	0.10
Fill	66.7 %	1.65
Eff.	3.48 %	
Series Res.	0.13 Ω	.023
60 lpi (23 cells)		
OCV	.470 V	.017
SCC	16.2 mA/cm^2	1.22
Pmax	5.10 mW/cm^2	0.63
Fill	67.3 %	0.28
Eff.	3.65 %	
Series Res.	0.13 Ω	.015
70 lpi (20 cells)		
OCV	.471 V	.028
SCC	16.1 mA/cm^2	1.28
Pmax	5.09 mW/cm^2	0.56
Fill	67.7 %	2.23
Eff.	3.64 %	
Series Res.	.12 Ω	.018
80 lpi (22 cells)		
OCV	.474 V	.021
SCC	15.7 mA/cm^2	1.38
Pmax	5.15 mW/cm^2	.36
Fill	69.1 %	3.77
Eff.	3.69 %	
Series Res.	0.11 Ω	.018

94

Table XLV.   Fill Factors of 50, 60, 70 and 80 lpi Gridded Cells by Substrate

Line Density	365-74	369-84	371-34	373-56	374-66	385-84	387-34	388-35	389-35	391-44
				-Substrate Number-						
50	67.1	65.1	67.8	69.2	68.5	66.8	68.3	64.2	67.9	69.5
50	66.4	64.9	64.9	67.2	67.5	66.5	68.0	64.0	67.6	67.4
50	--	--	--	62.8	—	--	65.8	--	--	--
50 lpi Ave.	(66.7	(65.0)	(66.4)	(68.2)	(68.0)	(66.7)	(66.4)	(64.1)	(67.8)	(68.5)
60	66.3	69.9	69.0	69.0	69.5	65.1	69.0	66.2	67.6	69.1
60	66.0	67.6	68.0	67.8	69.2	64.6	67.8	66.1	67.0	67.7
60	--	66.4	--	--	--	62.9	--	65.2	--	--
60 lsp Ave.	(66.2)	(67.6)	(68.5)	(68.4)	(69.4)	(64.8)	(68.4)	(65.8)	(67.3)	(68.4)
70	67.5	67.0	67.5	69.6	69.5	67.4	69.0	67.6	59.6	71.4
70	64.9	--	67.0	69.0	69.5	67.4	68.0	65.0	54.0	70.0
70	--	--	65.6	--	--	--	--	--	--	--
70 lpi Ave.	(66.2)		(66.7)	(69.3)	(69.5)	(67.4)	(68.5)	(66.3)	(56.8)	(70.7)
80	69.5	71.9	67.5	70.4	70.0	69.0	69.2	67.9	70.2	71.3
80	66.7	70.0	65.7	70.0	70.0	68.3	68.8	--	70.2	70.8
80	66.1	--	--	--	68.4	--	--	--	69.5	--
80 lpi Ave.	(67.4)	(71.0)	(66.6)	(70.2)	(69.5)	(68.6)	(69.0)	--	(70.0)	(71.0)
		Trend		Trend	Trend		Trend	Trend		

Hence, it can be concluded that a slight trend appears to exist, however, its magnitude is apparently so small that it does not seem to warrant changing the line density of the existing cells. It appears that a plot of series resistance vs. grid line density would increase monotonically until the density of the ideal grid is reached, i.e., a completely solid but transparent sheet of negligible resistance.

INTERLAYER SURFACE STUDIES

During the contractual effort immediately preceding the present one, an experimental substrate was investigated that had been commercially prepared by an outside vendor using a proprietary method of roll coating the Ag-Pyre ML layer onto the Kapton film. The cells fabricated from these substrates have been shown to result in a significantly higher performance level than cells fabricated from the standard sprayed substrate and with a much higher production yield.[1] Much effort has been expended in attempting to identify the difference between the two types of substrates with the hope that roll coated substrate performance could be duplicated with the standard sprayed substrate.

Scanning Electron Microscope Analysis. - Scanning electron microscope analysis of the two types of cells at various stages of fabrication through barrier formation was initially used in an attempt to detect any structural differences that may have been attributable to the difference in substrates. Small areas were punched out of each of the two types of cells after each process and submitted for SEM analysis. The remaining portions of the cells were processed into completed cells. The I-V characteristics of the roll coated cell showed an efficiency of 2.8% and a fill of 72% while the corresponding values for the spray coated substrate cell were 2.2% and 65.6%.

The two types of substrates were not handled exactly the same during substrate preparation. The roll coated substrates were cured at 250°C for 45 minutes after receipt from the vendor, while sprayed substrates were given a 375°C cure for 60 minutes. In addition, sprayed substrates were given a light burnish which roll coated substrates were not. Figure 32 shows a 3000X magnification SEM photograph of the as-received roll coated substrate and Fig. 33 shows it after its cure. Figure 34 shows the spray coated substrate after its cure but prior to the burnish treatment. Figure 35 shows the effect of the burnish treatment on sprayed substrates. . The substrates as shown in Figs. 33 and 35 are then zinc plated.

It was concluded from these photographs, and a sufficient number of others to warrant considering them as representative of the substrate at this stage of fabrication, that the main difference between roll coated and spray coated substrates was the relative amount of silver and varnish present on the surface. The roll coated substrate appeared to have approximately equal areas of silver and varnish on their surfaces while the spray coated substrates had a much greater area of silver. In retrospect it appears that the burnish operation even increased the silver area by removing some of the varnish. A number of attempts at reducing the amount of silver on sprayed substrates were subsequently made as a result of this information and their results are more fully described later.
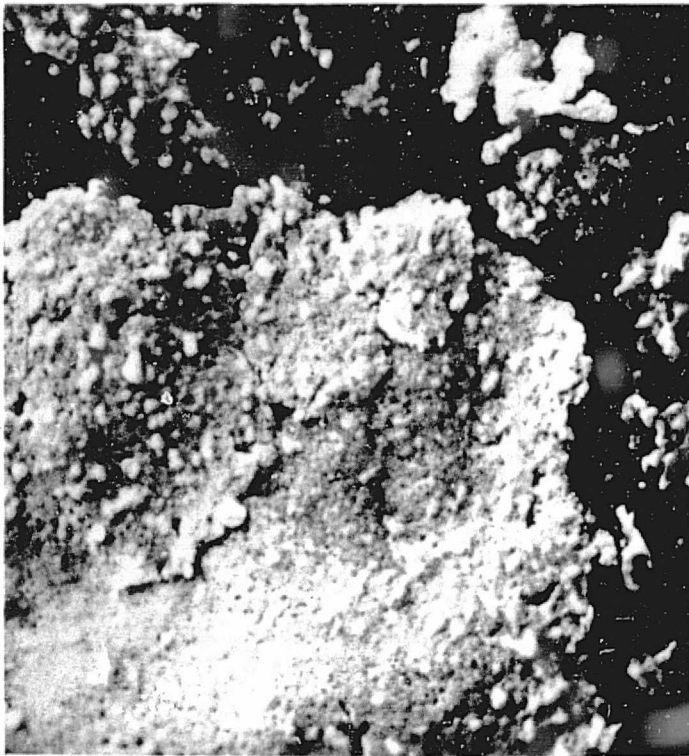
Fig. 32. Roll Coated Substrate Prior to Cure (as received). 3000X

Fig. 33. Roll Coated Substrate After Cure at 250°C for 45 Min. 3000X
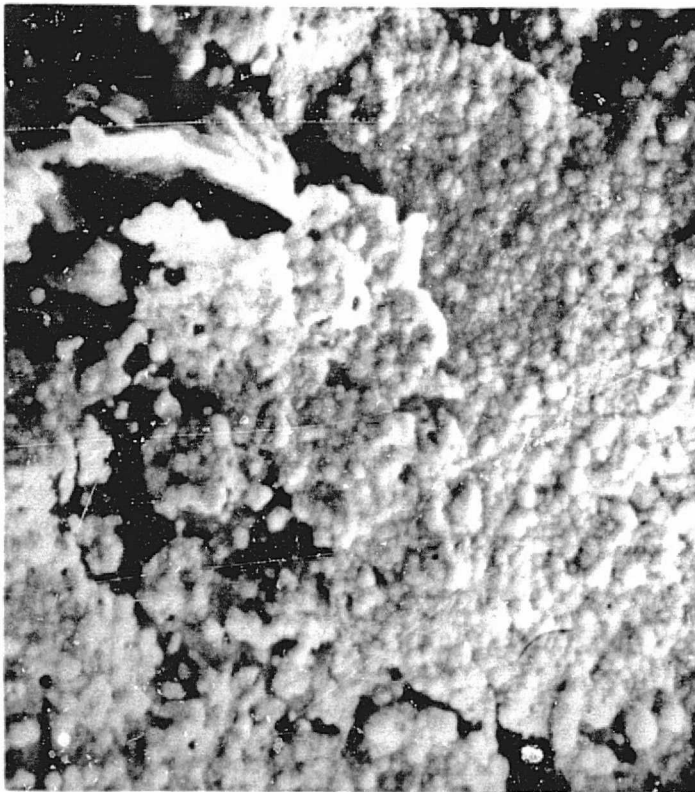

Fig. 34. Spray Coated Substrate Prior to Burnish. Cured at 350°C. 3000X

Fig. 35. Spray Coated Substrate After Burnish. 3000X

Figures 36 and 37 show photographs of the zinc plated substrates. The coarse flaky structure was rather surprising since a fairly smooth layered structure had been anticpated. It is assumed that the flakes are either zinc or silver-zinc alloys. The flakes of the roll coated sample appear to be larger and thicker and slightly less populous than the flakes on the spray coated sample. It was not known if this is the surface structure that the CdS film deposits on during the subsequent process of CdS evaporation. Zinc was known to alloy with silver and this could change the surface structure considerably from what appears in these photographs.

Figures 38 and 39 show photographs of the CdS film on the two types of substrates. The surface of Fig. 38 , the film on the roll coated substrate, bore considerably more resemblance to its substrate surface structure, Fig. 36 , than the CdS film on the spray coated substrate, Fig. 39, bore to its substrate surface, Fig. 37 . Since it was assumed that the one-mil thick CdS film ought to replicate the substrate surface partially at least it was tentatively concluded that the structure of the sprayed substrate, as shown in Fig. 37 , changed somewhat prior to the deposition of the CdS film. It will be shown more fully later that this change appeared to be the loss of free zinc, previously mentioned as a candidate responsible for the increase in series resistance due to its alloying with the silver during the preheat prior to the CdS evaporation process.

Figures 40 and 41 show the CdS films after the 5-second etch in HCl given immediately prior to immersion in the barrier solution. Figures 42 and 43 were taken after removal from the barrier solution. A difference between the barriered films on the two types of substrates is still readily apparent. The surface on the roll coated substrate film is more irregular and convoluted than the film on the spray coated substrate. In addition, the barrier operation has opened up holes and fissures which, in the case of the spray coated substrate film, appear quite parallel to one another and are assumed to extend quite deeply into the film and possibly down to the substrate. The holes on the roll coated substrate film are much more randomly oriented. It was concluded from this study that the CdS film on roll coated substrates has a structure that is more randomly oriented than the film on spray coated substrates. But the relation between CdS film structure and cell performance has never been adequately established. In fact, one would expect an improvement in the shunt resistance of the cell if a more randomly oriented CdS film were deposited, because the barrier layer would find it more difficult to form along the holes and fissures that the pre-etch apparently opens in the more vertically oriented film on spray coated substrates. However, an increase in shunt resistance is not among the attributes of roll coated substrate cells. The difficulty of associating the observed improvements of roll coated cells with the apparent increase in randomness of the CdS film structure quite naturally led to a consideration of whether or not the more easily studied substrate might by itself be the cause of the improved performance.

Duplication of Roll Coated Substrate Characteristics. - As mentioned previously the SEM photographs indicated that the ratio of exposed silver to varnish was much smaller on roll coated substrates than on spray coated substrates. The attempts at duplicating roll coated substrate characteristics on spray coated substrates initially centered around reducing the area of exposed silver on the
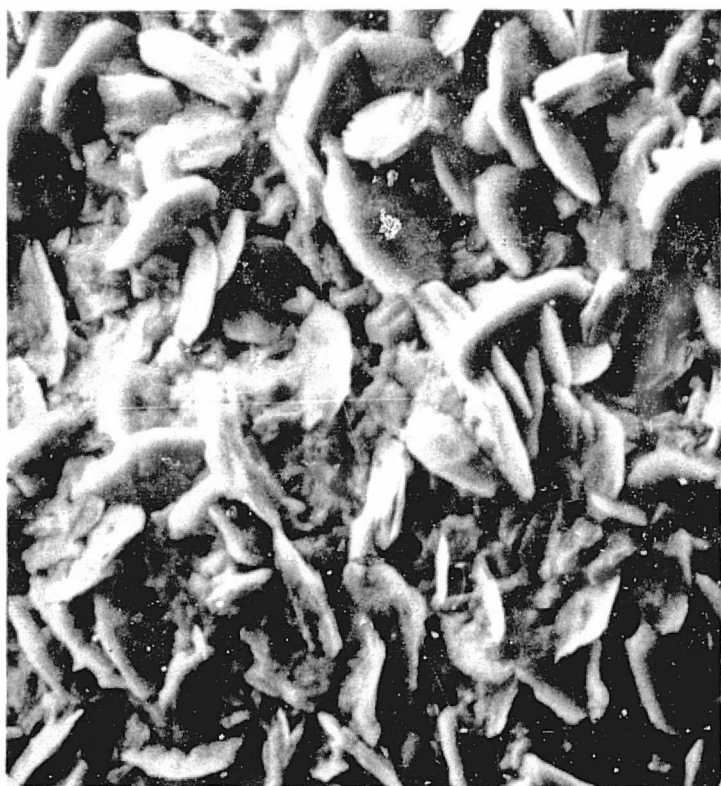
Fig. 36. Zinc Plated Roll Coated
Substrate. 3000X

Fig. 37. Zinc Plated Spray Coated
Substrate. 3000X

Fig. 38. CdS Film on Roll Coated
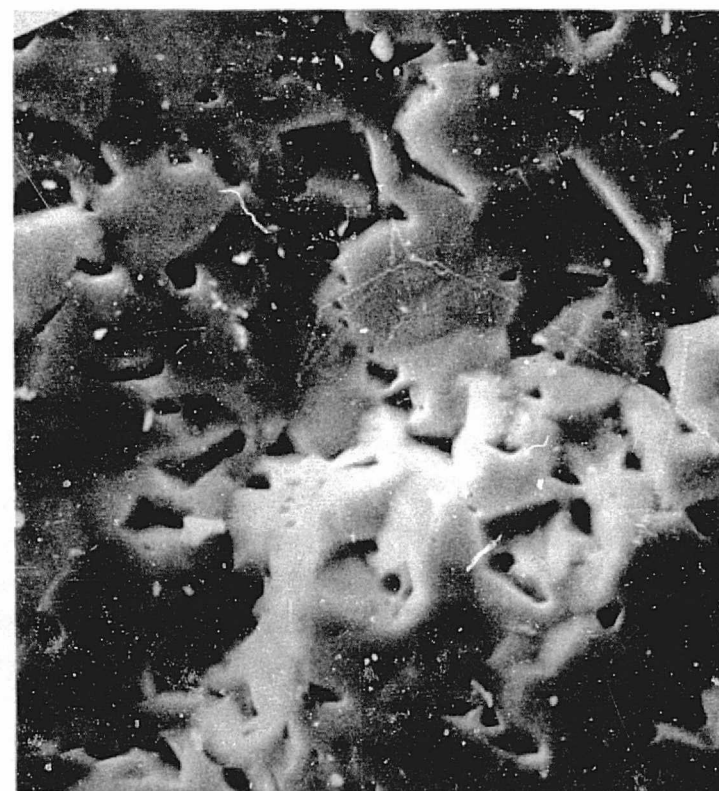Substrate. 3000X

Fig. 39. CdS Film on Spray Coated
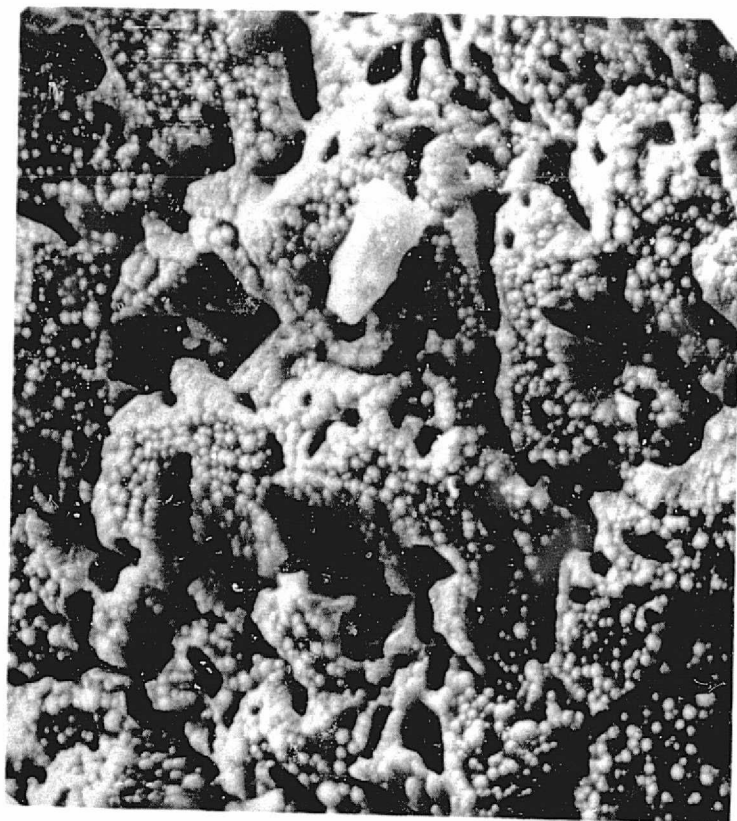Substrate. 3000X

Fig. 40.   Etched CdS Film on
    Roll Coated Substrate.   3000X
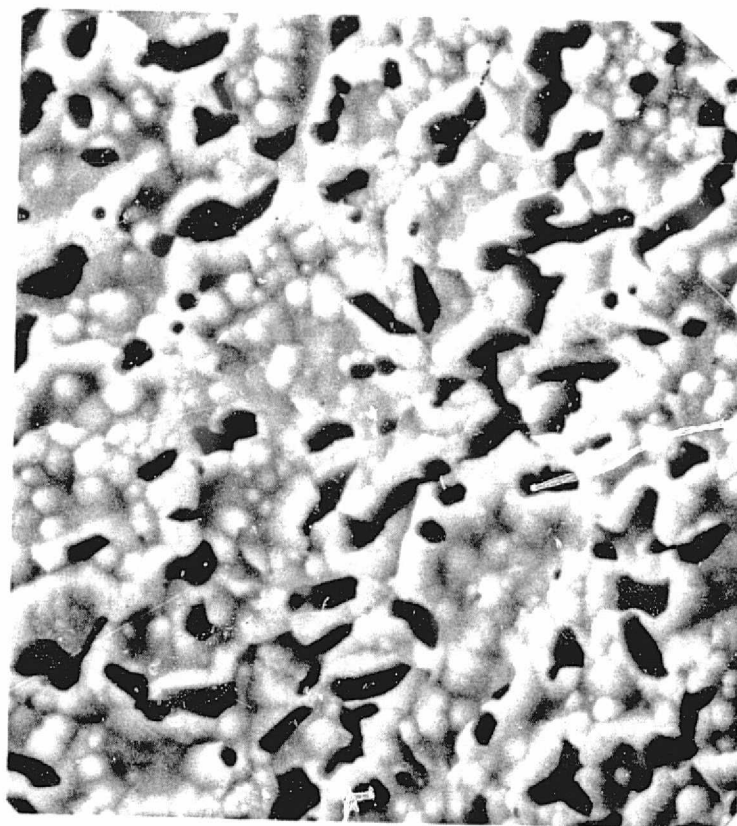

Fig. 41.   Etched CdS Film on
    Spray Coated Substrate.   3000X

Fig. 42.   Barriered CdS Film on
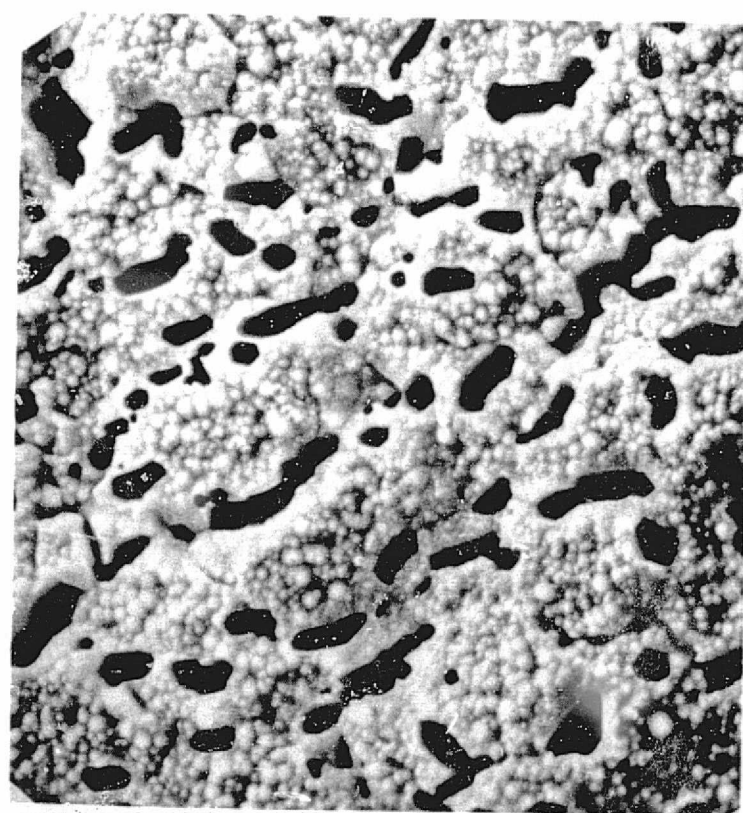   Roll Coated Substrate.   3000X

Fig. 43.   Barriered CdS Film
    on Spray Coated Substrate.   3000X

surface. This ratio is obviously not controlled during the actual process of silver deposition, be it roll coated or spray coated, because a mixture of one part silver powder to one part varnish has been found best for the roll coating process while a mixture of one part silver to two parts varnish is required for best results with the spray coating process. The actual silver to varnish surface areas must be determined after silver application. It was thought that by simply subjecting newly sprayed substrates to a silver etchant the amount of silver on the surface ought to be reduced according to the severity of the etch.

The preliminary attempts at etching a sprayed substrate in a dilute nitric acid solution were quite encouraging. The substrate was left in the acid until it had taken on a yellowish cast characteristic of roll coated substrates. Comparison with a roll coated substrate under a microscope revealed that indeed the two were almost identical. The etched substrate was then fabricated into otherwise standard process cells whose AM0-25°C parameters are listed in Table XLVI. .

Table XLVI. AM0-25°C Performance of Etched Substrate Cells

Cell No.	OCV	SCC	Efficiency	Fill
267351	.462	.854	3.5	69.6
2	.469	.880	3.7	68.8
3	.467	.766	3.2	69.9
4	.471	.913	3.8	68.9
5	.460	.880	3.6	69.3
6	.461	.861	3.6	70.2
7	.463	.820	3.5	71.5
8	.461	.840	3.4	68.8
9	.468	.847	3.6	69.9
Average	.465	.851	3.5	69.7

The results were obviously encouraging enough to warrant a more systematic study. Four freshly prepared sprayed substrates were etched in a weak ferric nitrate solution for times that varied from 2 minutes to 5 minutes in one minute intervals. All of the substrates again took on the characteristic yellow cast of roll coated substrates. Table XLVII describes the AM0-25°C performance of the resulting cells.

Table XLVII.   AM0-25°C Performance of Etched Substrate Cells

Cell No.	OCV	SCC	P_{max}	Eff.	Fill	
359-2V1	Shorted					
2	.471	.883	.269	3.6	64.8	
3	.487	.817	.245	3.2	61.6	
4	Shorted					5 Minute etch
5	.481	.812	.241	3.2	61.6	
6	.472	.795	.206	2.7	55.0	
357-8V1	Shorted					
2	.469	.801	.221	2.9	58.7	
3	.481	.799	.236	3.1	61.4	
4	.469	.770	.198	2.6	54.8	4 Minute etch
5	.467	.783	.245	3.2	66.9	
6	Shorted					
357-7V1	Shorted					
2	.462	.800	.241	3.1	65.1	
3	.458	.772	.216	2.8	61.1	
5	.462	.780	.238	3.1	66.0	3 Minute etch
6	.460	.790	.222	2.9	61.1	
357-6V1						
2						
3	All heavily copper					
4	precipitated during					2 Minute etch
5	barrier formation.					
6						

Cell performance at best is quite mediocre. Although the OCV's and SCC's seem fairly normal, the cells are characterized mainly by low fills. The prevalence of shorted cells and the loss of an entire substrate due to copper precipitation indicate that a shunting problem is present. Figure 44 shows the I-V trace of the cell with the highest fill. The poor shunt characteristic appears to be more dominant than the poor series resistance. However, it is difficult to reconcile etching of the substrate with a shunting problem on the barriered CdS film. But this is characteristic of CdS films on roll coated substrates.

The attempt was repeated again on eight sprayed substrates, which were etched by pairs in the ferric nitrate solution for 2, 3, 4, and 5 minutes. They were processed into completed cells, but treated as roll coated substrates which they were designed to approximate. The barrier etch time was accordingly reduced to about one second. Table XLVIII shows the averages of the AM0-25°C performance parameters of the resulting cells. Also shown are the results of two standard process substrates that were barriered during the following barrier lot.
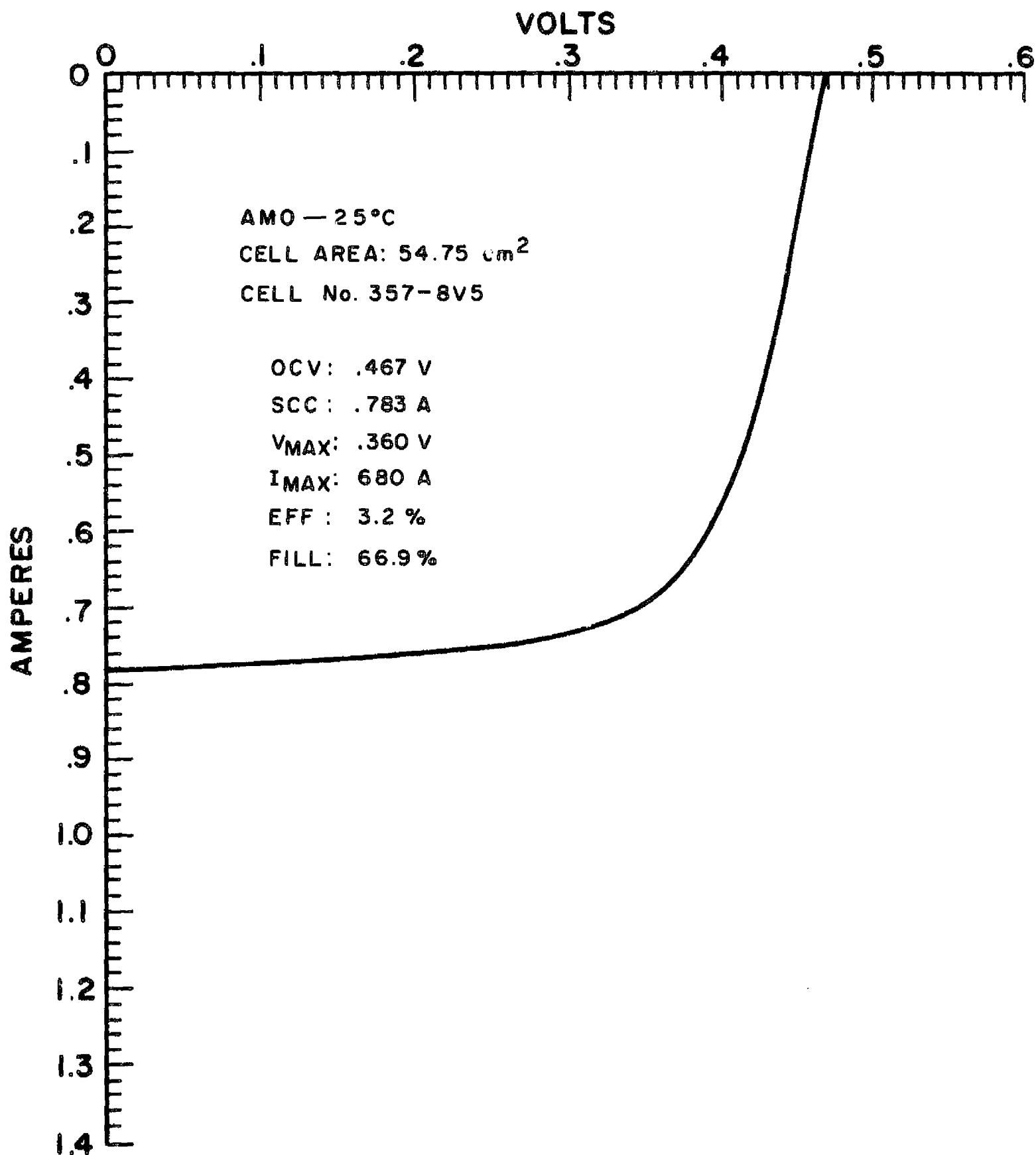
FIG. 44: AMO−25° C PERFORMANCE OF CELL WITH
ETCHED SUBSTRATE.

Table XLVIII. Averaged AM0-25°C Performance of Etched Substrate Cells

Etch Time Min.	OCV V	SCC A	Eff. %	Fill %	No. of Cells
2	.474	.772	3.2	67.4	11
3	.471	.778	3.2	66.5	12
4	.472	.764	3.2	67.5	12
5	.473	.780	3.3	67 6	11
Standard Process	.479	.795	3 4	68.8	6
Substrate Cells	.481	.767	3.3	68.2	7

Since the average performance of the etched substrate cells is not significantly different from the averaged performance of the standard process cells, it would appear that duplicating the silver-varnish ratio of roll coated substrates is by itself insufficient duplication of roll coated substrate characteristics. The fact that roll coated substrate cells normally show a higher SCC and fill than standard process cells in spite of the reduced barrier etch time, is indication of yet another significant difference between roll coated and spray coated substrates. This implies that perhaps the previously mentioned structural differences between CdS films evaporated on the two types of substrates are more significant than any differences in the substrates themselves.

In a related set of experiments an attempt was made to vary the ratio of silver to varnish exposed on the substrate surface over a wide range to determine if an optimum value existed Silver foil, 0.65 mil thick and laminated to Kapton film, was used as the starting substrate. Varying ratios of silver to varnish were obtained by etching away controlled amounts of the silver foil. This was done by exposing a layer of photo resist on the foil through a sheet of photographer's screen tint. The developed layer of photo resist then served as the mask during subsequent etching of the foil. Screen tint is available in a wide range of light transmission and line densities and the desired range was readily covered.

The initial attempts resulted in uniformly etched foil substrates that were 10 to 20% light transmissive. However, the 85 line per inch pattern was much too coarse a pattern for the evaporated CdS to bridge and form a smooth film. The CdS film very faithfully replicated the perforated substrate pattern, but did not survive the barrier operation, abnormal amounts of copper precipitation resulted. Increasing the line density to 135 lines per inch, and later to as high as 300 lines per inch, still resulted in too coarse a substrate pattern for the CdS to form a smooth continuous film.

Substrate Resistance - Effect of Zn Plating. - The zinc plated substrate is subjected to a 220°C bake out prior to CdS evaporation for times that vary from a few minutes to up to an hour. This time is determined by the pump-down speed of the large production evaporator which in turn is obviously dependent on the cleanliness of the system. The effects of this varying bake out time are unknown but have been suspected of resulting in variations in the thickness of the zinc interlayer, as a result of either evaporation of the zinc or by alloying with the silver in the silver Pyre ML layer, or both. It was mentioned previously that there is doubt as to the existence of any free zinc on the substrate surface by the time the CdS deposition process begins.

In order to more thoroughly understand the process zinc plated sprayed and roll coated substrates were heated in 5 minute increments at 220°C in vacuum. After each 5 minute interval a 3 x 3 inch portion was removed and small samples from each were cut out and submitted for X-ray and scanning electron microscope analysis.

The SEM photographs of the samples heated for 5 minutes, Figs. 45 and 46 revealed that the roll coated and spray coated substrates were already significantly different. The roll coated substrate, Fig. 45 , shows the same well defined flakes standing on edge seen previously. However, the spray coated substrate, Fig. 46 , shows a much flatter and more uniform surface, with randomly scattered protrusions that apparently indicate the prior existence of free standing flakes. The sequence of photographs revealed little change as the heat exposure time was increased for both substrates. The assumed flakes of free zinc were just as prominent and well defined on the roll coated substrate after 40 minutes exposure, Fig. 47 , as they were after the initial 5-minute exposure. The spray coated substrate, Fig. 48 , similarly retained its 5-minute characteristics.

This experiment indicates that there is a significant difference between roll coated and spray coated substrates in the amount of free zinc present on their surfaces when the CdS deposition process begins. Roll coated substrates appear to retain their zinc interlayers as free zinc for longer time periods and at higher temperatures than sprayed substrates. In fact, it appears that the zinc interlayers on standard sprayed substrates is extremely sensitive to treatment after plating and can disappear even at room temperature within a matter of hours.

X-Ray Analysis of Roll Coated and Sprayed Substrates. - The results of X-ray studies of portions of the same samples correlated rather well with the findings of the scanning electron microscope analysis. Again, no free zinc was present on the spray coated substrate samples, only free silver and various silver-zinc alloys were detected. There was a tendency towards an increase in the high silver compounds, Ag_5Zn_8 and $AgZn$, at the expense of a decrease in the high zinc content alloy, $AgZn_3$, as the heating time was increased. The tendency was not strong, however, and there was almost as much variation between adjacent samples as there was over the series of nine heating times. A reduction in high zinc alloys is not unexpected if the quantity of zinc initially deposited was quite small relative to the quantity of silver and merely indicates continued diffusion of the zinc to a more uniform distribution in the Ag-Pyre ML layer.

105

Fig. 45.   Zn Plated Roll Coated
   Substrate After 5 Min. at 220° C
   in Vacuum.   3000X

Fig. 46.   Zn Plated Spray Coated
   Substrate After 5 Min. at 220° C
   in Vacuum.   3000X

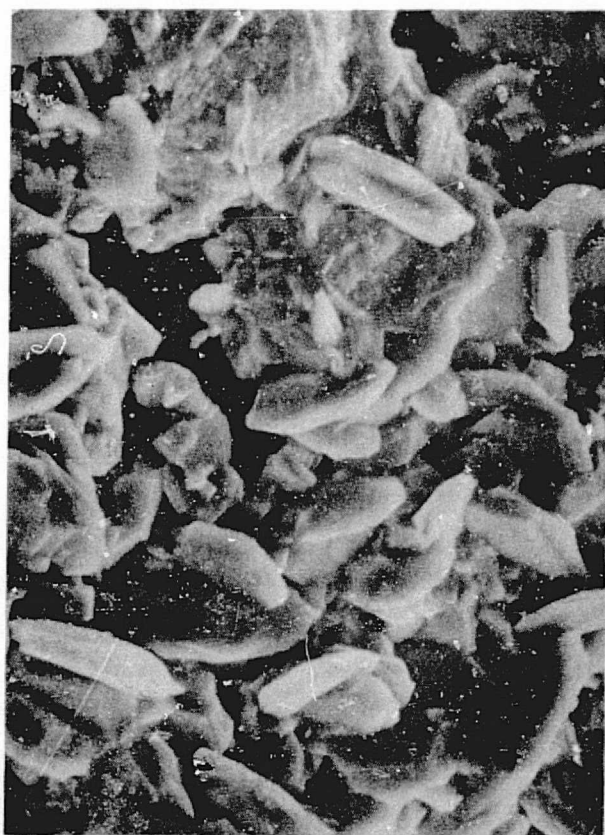Fig. 47.   Zn Plated Roll Coated
   Substrate After 40 Min. at 220° C
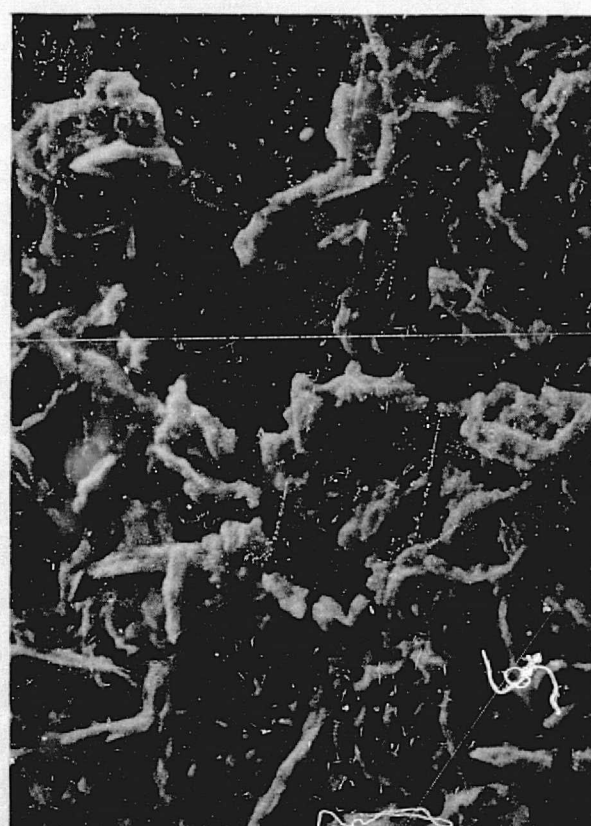   in Vacuum.   3000X

Fig. 48.   Zn Plated Spray Coated
   Substrate After 40 Min. at 220° C
   in Vacuum.   3000X

In addition to those alloys just listed for the sprayed substrate, free zinc was also detected on all the roll coated specimens. Silver and zinc noticeably decreased with increasing time of exposure, with zinc down to about 75% of its 5-minute value after 45 minutes of accumulated heat treatment. The three silver-zinc alloys all increased with increasing exposure time. $AgZn_3$ started to show a decrease at the end. Assuming that the free zinc was just beginning its diffusion process into the Ag-Pyre ML layer, increasing values of all the alloys should be expected.

Previous X-ray studies on roll coated and spray coated samples indicated that the life of free zinc on spray coated substrates was quite varied. In fact, one sample showed no free zinc when analyzed immediately following zinc plating. Another sample showed a substantial reduction in the intensity of the free zinc lines as a result of a 6-hour room temperature exposure, while yet another sample showed a substantial amount of free zinc after 6 days at room temperature. Free zinc was detected on all roll coated samples up to mounting in the CdS evaporator, but its presence has never been detected after CdS evaporation on either type of substrate. But it should not be concluded that it is not present; it merely has not been detected. A valid detection procedure requires the preparation of samples on which the CdS layer has been removed without disturbing the substrate. Separation at the substrate-CdS film interface has never been accomplished on roll coated cells without some damage to either one or the other layer.

Substitute Substrates. - In order to determine if the substrate itself was the cause of the increased series resistance, attempts were made to reduce the substrate resistance on finished cells by paralleling their existing substrates with metal foil. Very careful experiments in which silver foil was cemented in parallel with the silver Pyre ML substrate did indeed indicate that a reduction in series resistance occurred. The procedure followed was to cement glass plates to the front surface of the cells with a clear epoxy. The Kapton plastic was then stripped from the backs of the cells and only those cells whose Ag-Pyre ML layers remained attached to the CdS layers on the cells were used further. Silver foil, 0.65 mils thick was then attached to these original intact Ag-Pyre ML layers with room temperature curing conductive silver epoxy.

Figure 49 shows the AMO-25°C I-V characteristics of a typical cell so treated. Curve 1 is the initial curve obtained after the cell had been cemented to the glass plate. Curve 2 was obtained after the back Kapton plastic had been stripped off while Curve 3 was obtained after the silver foil had been epoxied in place. The improvement in the series resistance and fill is readily apparent.

Seven cells were so treated and Table XLIX shows the tabulated AMO-25°C results. Only Cell 343-651E showed no improvement as a result of the treatment. Somewhat surprisingly all parameters on the remaining six cells improved, even the OCV. However, the increased OCVs could very easily have been due to thermal effects, since the glass mounted cells did not make the same thermal contact to the cooling block in the cell tester that normal cells do.

107

VOLTS

AMO — 25° C
CELL AREA: 54.75 cm^2
CELL No. 343-653

AMPERES
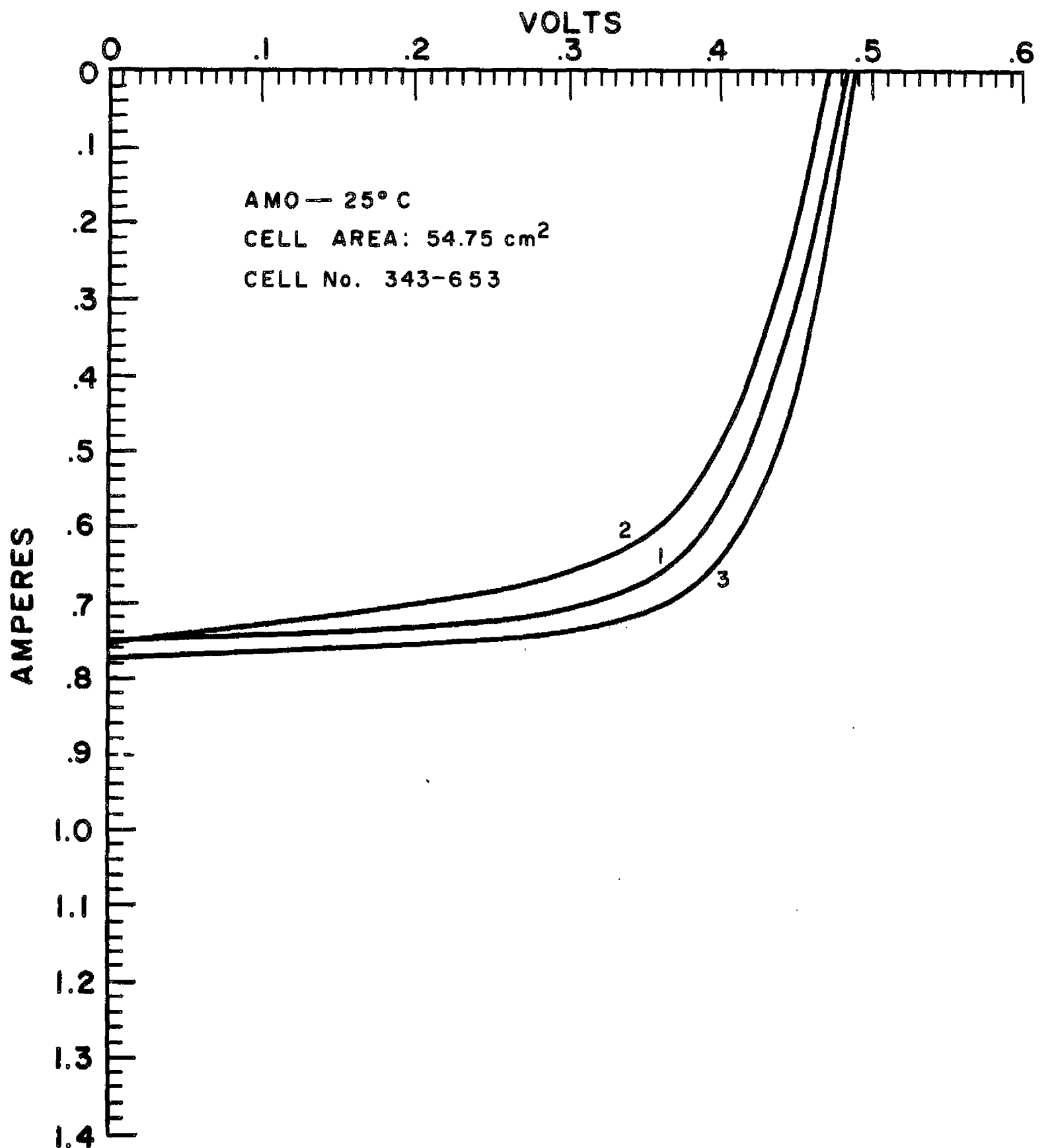
TIME	OCV	SCC	P$_{MAX}$	FILL	EFF.	I$_{MAX}$	V$_{MAX}$	REMARKS
1	481	751	237	65.5	3.1	640	370	AFTER MOUNTING
2	469	753	214	60.5	2.8	602	355	AFTER STRIPPING BACK
3	489	776	260	68.6	3.4	667	390	WITH NEW SILVER FOIL BACK

FIG. 49:   I-V CURVE AMO–25°C FOIL REINFORCED CELL.

ERD 8251

Table XLIX.   Effect of Paralleling Existing Substrates with Silver Foil

| Cell No.		OCV	SCC	Pmax	Fill	Eff.
343-349F	Before	.488	.699	.227	66.5	3.0
	After	.499	.721	.249	69.2	3.3
343-567F	Before	.478	.717	.233	67.8	3.1
	After	.486	.724	.248	70.4	3.3
343-569F	Before	.485	.740	.243	67.8	3.2
	After	.492	.767	.264	70.0	3.5
343-651E	Before	.475	.799	.256	67.6	3.4
	After	.479	.823	.258	65.3	3.4
343-652E	Before	.483	.780	.250	66.4	3.3
	After	.488	.791	.266	68.8	3.5
343-653E	Before	.481	.751	.237	65.5	3.1
	After	.489	.776	.260	68.6	3.4
343-654E	Before	.479	.722	.234	67.6	3.1
	After	.485	.743	.252	70.0	3.3

When the results of the X-ray analysis and the scanning electron micro-
scope analysis are considered along with these data it appears that the alloying
of the free zinc with the silver in the Ag-Pyre ML substrate is resulting in an
increased substrate resistance. Even though the resistivity of the Ag-Pyre ML
layer may be well within its specified value when initially prepared it appears
that it could very well be increasing after zinc plating and during subsequent
cell processing, particularly during the time interval between zinc plating and
CdS evaporation. In fact there is no assurance that the alloying process does
not continue after CdS evaporation, even after cell fabrication has been com-
pleted. This mechanism could account for some of the series resistance in-
crease seen on high temperature vacuum storage as already mentioned.

The apparent ability of roll coated substrates to retain free zinc longer·
than sprayed substrates may lie with the differences in the ratios of silver to
varnish areas exposed on their surfaces. This difference, which has been dis-
cussed earlier means that the zinc on roll coated samples is in contact with a
smaller area of silver than is the case of zinc on sprayed samples. Since the
same quantity of zinc is deposited on both types of substrates, it follows that
it should take a longer time for the zinc on the roll coated samples to alloy with
the silver than for the zinc on the sprayed substrates.

Variation in Substrate Resistance. - A series of experiments was then con-
ducted in which the resistance of roll coated and standard sprayed substrates,
both zinc plated and bare, was followed as a function of time at temperature.
Figures 50 and 51 show how the resistance of zinc plated roll coated and sprayed
substrates varied as a function of time at 220°C. The samples were removed at
10 minute intervals for room temperature resistance measurements. For com-
parison, Figs. 52 and 53 show how the resistance of roll coated and sprayed
substrates with no zinc plate varied. Although these experiments were done in
an air oven, the results are expected to be equally valid in vacuum.

The fact that the zinc plated sprayed sample showed a significant increase
in resistance, Fig. 51 , while the zinc plated roll coated sample remained fairly
constant, Fig. 50 , and the fact that the unplated sprayed sample showed very
little change, Fig. 53 , indicate that the zinc interlayer does indeed affect sub-
strate resistivity. The curves shown in Figs. 51 and 53 were obtained from
samples from the same spray coated substrate while the curves shown in
Figs. 50 and 52 were obtained from samples from the same roll coated sub-
strate. Half of each substrate was zinc plated, and the four substrate halves
were cut into four 2 x 5 inch samples which were used for the experiment. The
curves shown in the figures are very similar to the other three obtained from
the same group of four specimens, e.g., the curve in Fig. 51 was almost
identical to the curves obtained from the other three zinc plated sprayed samples.

It was assumed that if the previously mentioned alloying mechanisms were
truly responsible for the observed increase in substrate resistance, then simply
avoiding any contact between the zinc and the silver ought to eliminate the prob-
lem. Accordingly, the resistance of a multilayer substrate construction, in
which a third layer, interposed between the Ag Pyre ML layer and the zinc layer,
and acting as a barrier to the migration of both, was measured under the pre-
vious conditions. A 1000 Å thick layer of chromium was electroplated over both
burnished and nonburnished sprayed Ag Pyre ML substrates. The standard
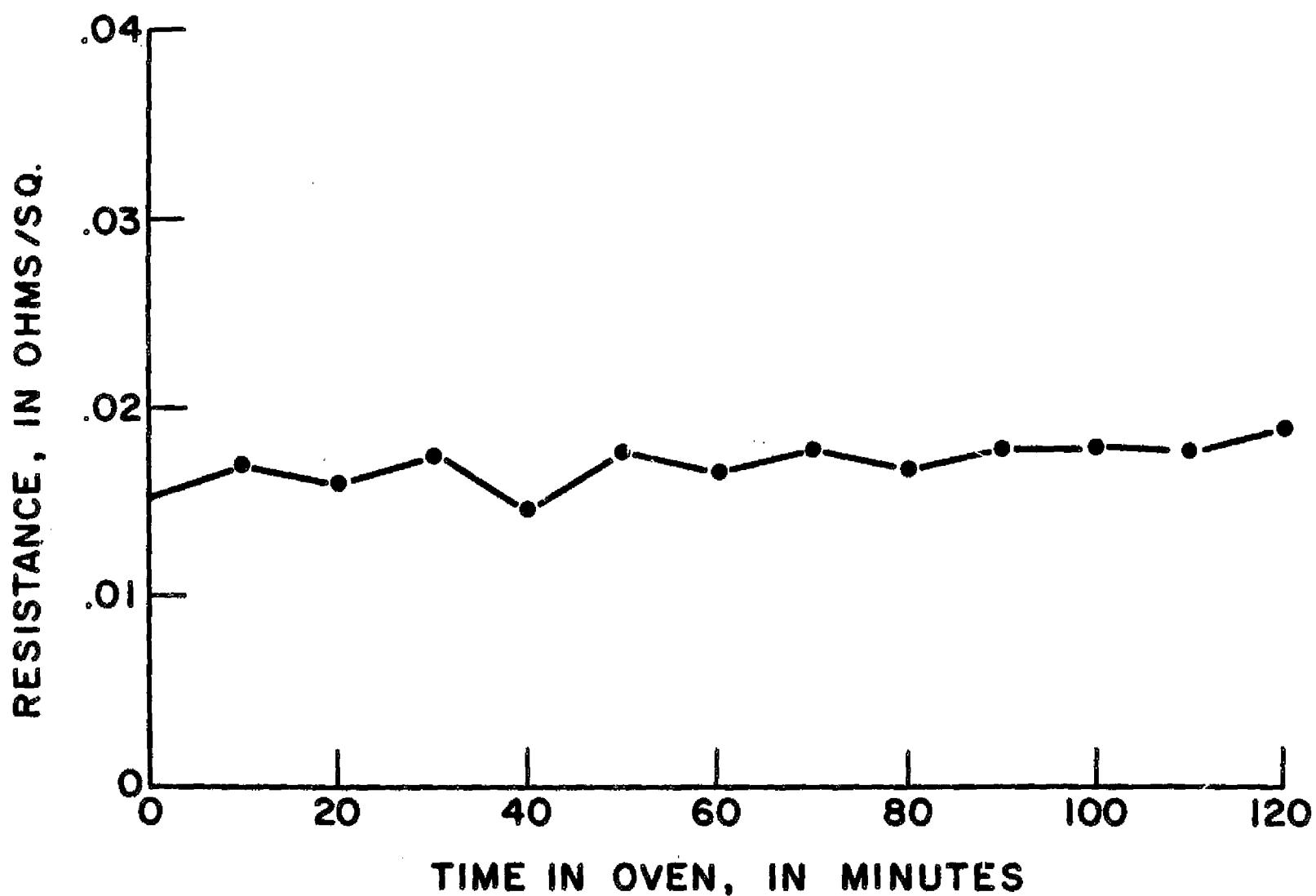
FIG. 50: RESISTANCE OF ZINC PLATED ROLL COATED SILVER SUBSTRATE vs. TIME IN 220°C OVEN.
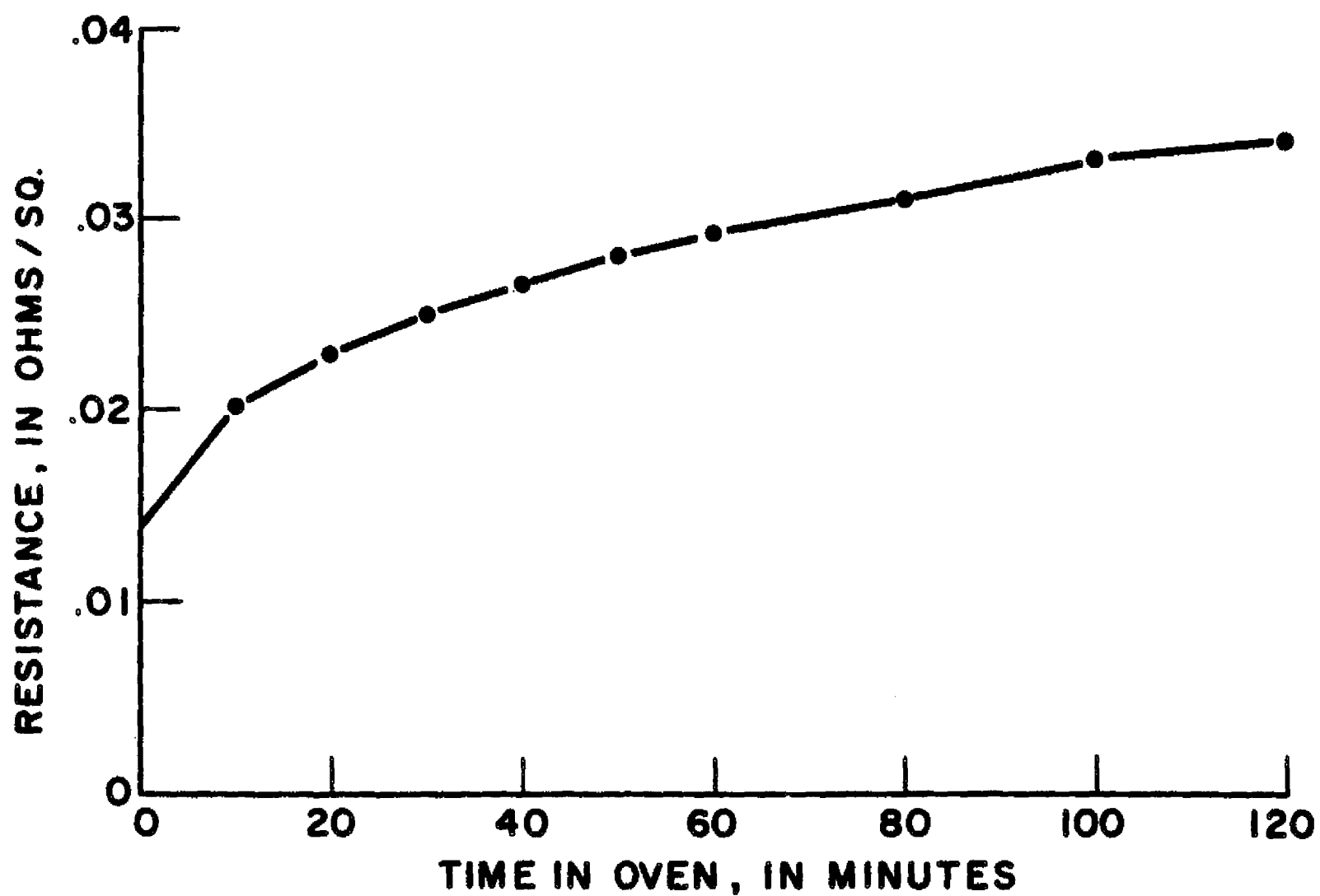
FIG. 51: RESISTANCE OF ZINC PLATED SPRAYED SILVER SUBSTRATE vs. TIME IN 220°C OVEN.

112   ERD 8253
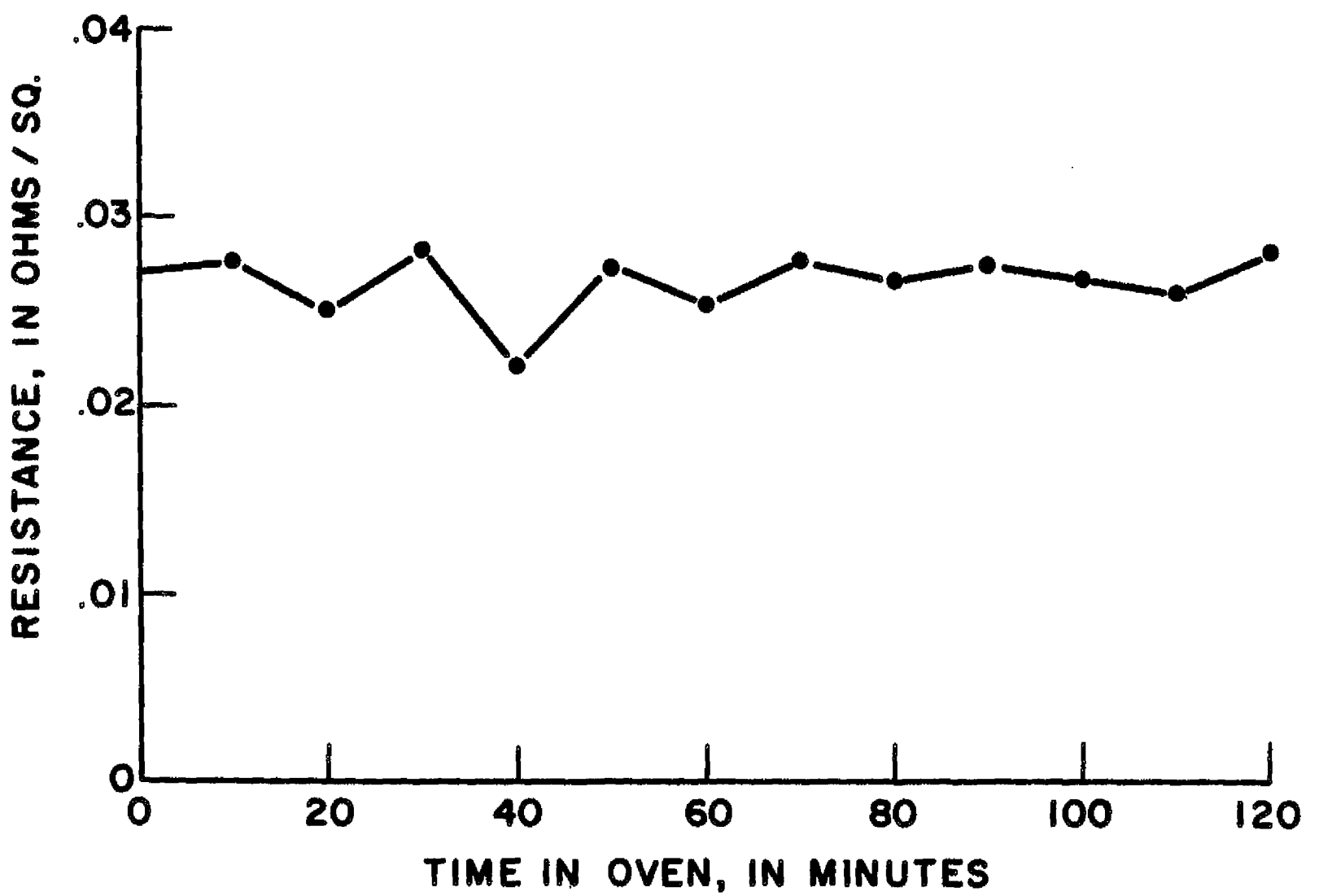
FIG. 52: RESISTANCE OF ROLL COAT SILVER SUBSTRATE vs. TIME IN 220°C OVEN.

113

FIG. 53: RESISTANCE OF SPRAYED SILVER SUBSTRATE
vs. TIME IN 220°C OVEN. NO ZINC PLATE.

ERD 8255

FIG. 54: RESISTANCE OF TWO ZINC PLATED, CHROME PLATED, UNBURNISHED, SPRAYED SILVER SUBSTRATES vs. TIME IN 220°C OVEN.

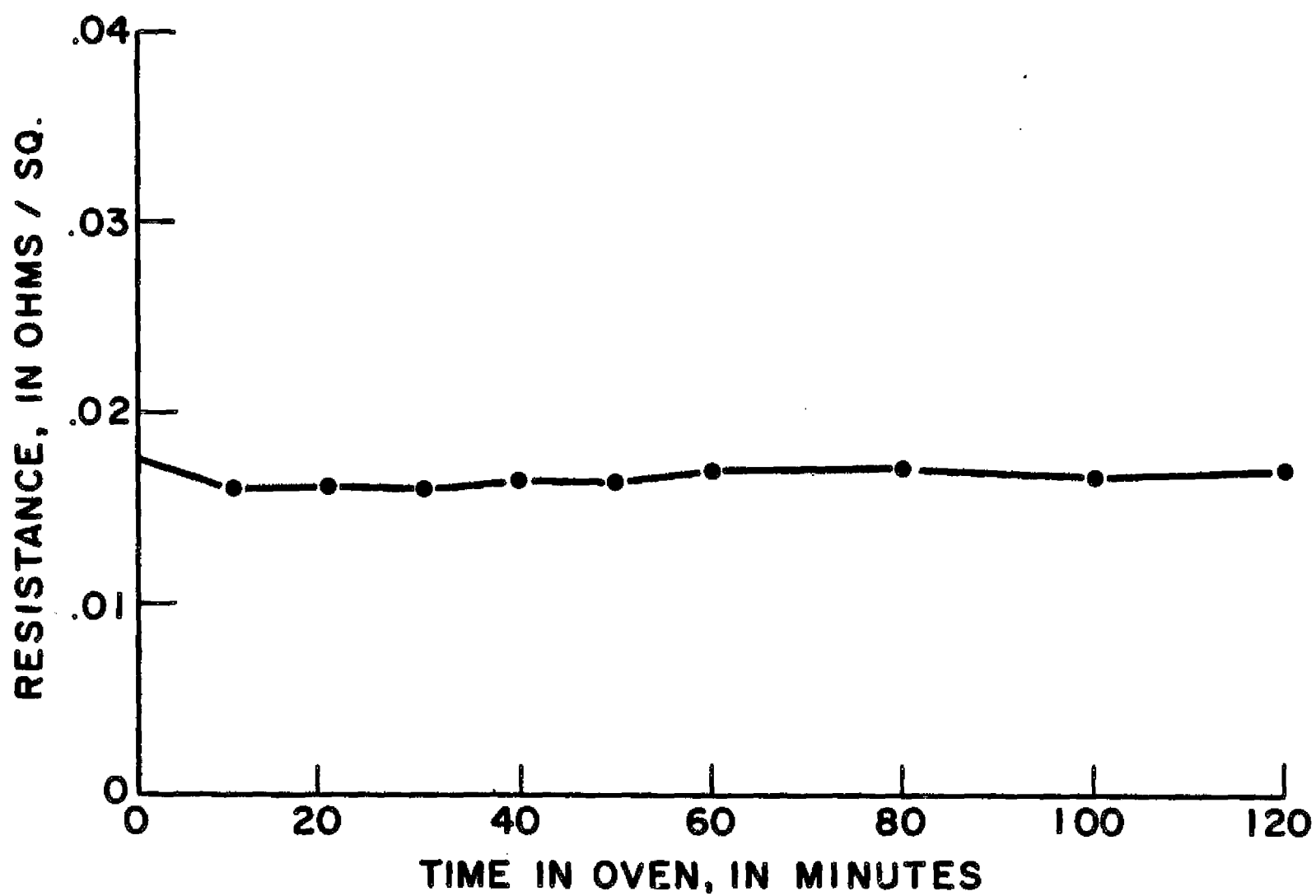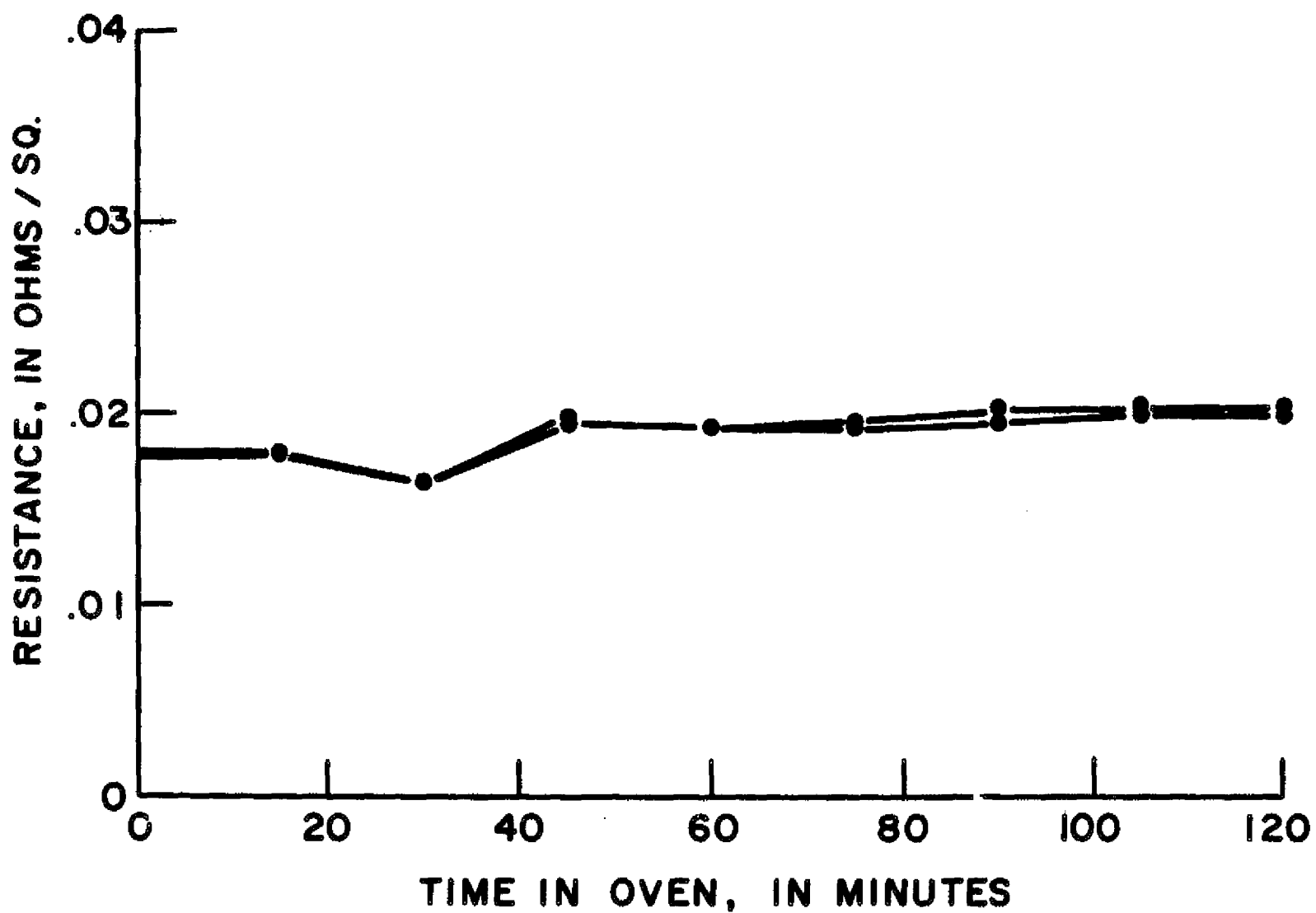zinc plate was then applied over the chrome layer. Chromium was selected for the first attempt because of its inertness. Surprisingly, little difficulty was experienced in zinc plating over the chrome plate. Figure 54 shows the results for two of the unburnished samples; similar results were obtained from the burnished samples. These results obviously indicate that the resistance of these trilayer substrates is more stable than sprayed substrates shown in Fig. 51 . This implies that the chrome layer is somewhat effective as a barrier to the alloying process.

It was then attempted to fabricate cells using the chrome trilayer substrates. A layer of chromium about 1000 Å thickness, was electroplated onto 4 standard process substrates, two of which were burnished and the other two unburnished. The chrome plated substrates were then given the standard zinc plate, and were subsequently processed into completed cells, standard process in all respects other than the chromium layer in the substrate.

Table L shows the AM0-25°C performance parameters, averaged by substrate, of the resulting completed cells. Also shown are the averages of two standard process substrates that were evaporated and barriered simultaneously with the trilayer substrates. Figure 55 shows the I-V characteristic of a typical cell. A somewhat higher than normal series resistance appears to be characteristic of these trilayer cells. Also, their SCC's and efficiencies were lower than the standard process cells while their fills were higher. A higher series resistance in these cells is difficult to reconcile with the normal substrate resistance observed during the previously mentioned resistance versus heat treatment studies. However, it is quite possible that the increased cell series resistance can be attributed to causes other than the substrate. It is not known if the CdS film that was deposited on these substrates differed from films deposited on standard process substrates in any way. It may be that the resistance of the barrier layer formed on these films is higher than normal. Examination under the highest magnification on an optical microscope however revealed little difference between the trilayer substrates and standard process substrates.

Table L . Performance of Trilayer Substrate Cells.
(Averaged According to Substrate.)

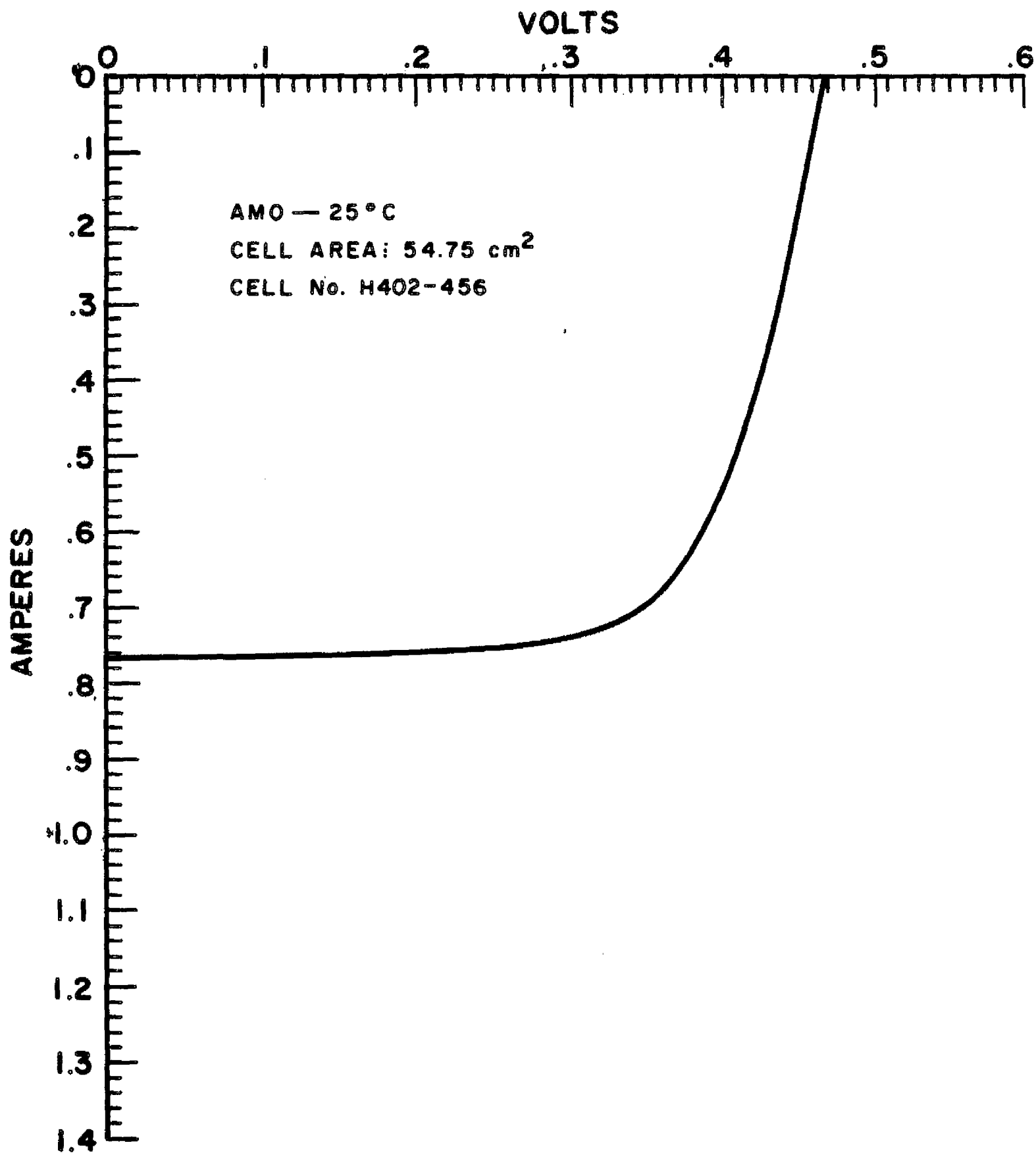| SS No.	Burnished or Unburnished	OCV V	SCC A	P_{max} W	Eff. %	Fill %	Rseries Ω	No. of Cells
402-35	U	.451	.641	.195	2.5	67.6	.106	5
402-45	U	.469	.752	.241	3.1	68.1	.094	9
402-56	B	.467	.749	.237	3.1	67.8	.096	9
402-64	B	.468	.743	.235	3.1	67.8	.101	5
401-5 & 6	*	.478	.887	.276	3.6	66.0	.081	10

*Standard process.

116

FIG. 55 : PERFORMANCE OF TRILAYER SUBSTRATE CELL

117

Variations in the Thickness of the Zinc Interlayer. - If the amount of free zinc that remains on the substrate surface is truly the essential difference between roll coated and spray coated substrates, then simply increasing the thickness of the zinc plate that is deposited during the preparation of standard spray coated substrates ought to increase the length of time that unalloyed zinc is present. In order to test the validity of this hypothesis the zinc plating time was varied from a half-minute to 5 minutes on a group of six substrates. The standard process specifies a zinc plating time of 1 minute at a current density of 370 mA/in^2. The current density was kept constant while plating times of 1/2, 1, 1-1/2, 2, 3 and 5 minutes were used. The AM0-25°C performance averages by substrate of the resulting cells are shown in Table LI.

Table LI.   Effect of Zinc Plating Time on AM0-25°C Performance. Averaged by Substrate.

Plating Time	OCV V	SCC A	P_{max} W	Eff. %	Fill %	Cell No.
1/2 min.	.465	.620	.196	2.56	68.1	9
1 min.	.465	.660	.213	2.78	69.5	8
1-1/2 min.	.475	.769	.242	3.16	66.3	9
2 min.	.468	.830	.268	3.49	69.0	7
3 min.	.461	.849	.266	3.47	68.0	9
5 min.	.467	.903	.279	3.64	66.9	8

Somewhat unexpectedly there is a correlation between SCC and maximum power and plating time. If the amount of free zinc were affecting the substrate resistance, as suspected, then an increasing fill with increasing plating time should have resulted. No definite correlation between fill and plating time is apparent; if anything, there is an indication of a maximum only at the center of the range. The increase in SCC and maximum power is apparently the result of the effect of the plating time variation on the CdS film structure, or some other, as yet unknown, manifestation of the increased thickness of the zinc layer. It could very well have been that the decreased substrate resistance was overshadowed by an increase elsewhere in the series resistance, such as an increase in barrier layer resistance caused by the change in substrate surface structure.

HEAT TREATMENT STUDY

Contract NAS3-13467 was modified in December of 1970 to include an experiment under which freshly barriered substrates were exposed to carefully controlled conditions of temperature, time, and atmosphere before being completed as cells. The experiment was designed by NASA [8] to determine the optimum conditions for time and temperature exposure to air to "form up" the cells most favorably. Seventy two substrates were treated according to the program shown in Table LII and were subsequently made up into cells.

In performing the heat treatments, it was planned that barriered substrates dried under an argon jet would either be exposed at once to the environment specified, or would be stored in a sealed container in an argon atmosphere until they could be processed. Experience soon showed that substrates so stored showed abnormally large losses from copper precipitate, due apparently to large quantities of moisture still adsorbed on the rough etched surface. Storage therefore took place under mechanical pump vacuum at room temperature, which completed the drying very promptly. Also, substrates that were to receive a very short heat treatment in vacuum had to be dried first in room temperature vacuum, since the drying operation greatly delayed temperature stabilization in the high temperature vacuum oven. The particular process steps encountered by each substrate were noted on the individual data sheets.

All the cells were subsequently completed and tested. In a few cases, a large spread in performance was noted among the cells of the same substrate due apparently to some anamoly in the processing and substitute substrates were run at these conditions.

The performance characteristics of the cells were averaged for each substrate, disregarding occasional single bad cells. The values so obtained are shown in Table LIII for cells treated in air and Table LIV for cells treated in vacuum.

The test data and the cells were delivered to NASA, Lewis, where a computer analysis will be run. No attempt has been made to draw conclusions in advance of that analysis.

Table LII. Optimum Seeking Experiment for the Post Barrier
Heat Treatment Process.

| Treatment | Variables | | |
Combination	Temperature (°C)	Time (Minutes)	Environment
Phase "A"			
Center Point (V)*	118	430	Vacuum
Center Point (A)*	118	430	air
Cube Points:			
(1)	103	199	Vacuum
a	133	199	Vacuum
b	103	930	Vacuum
a b	133	930	Vacuum
c	103	199	Air
a c	133	199	Air
b c	103	930	Air
a b c	133	930	Air
Star Points:			
T_1V	97	430	Vacuum
T_2V	140	430	Vacuum
t_1V	118	147	Vacuum
t_2V	118	1255	Vacuum
T_1A	97	430	Air
T_2A	140	430	Air
t_1A	118	147	Air
t_2A	118	1255	Air

(Continued)

*four runs at this condition.

Table LII. Optimum Seeking Experiments for the Post Barrier
Heat Treatment Process   (Continued)

Treatment Combination	Variables		
	Temperature	Time (Minutes)	Environment
Phase "B"			
Center Point (V)*	165	50.2	Vacuum
Center Point (A)*	165	50.2	Air
Cube Points:			
(1)	147	23.3	Vacuum
a	186	23.3	Vacuum
b	147	108	Vacuum
a b	186	108	Vacuum
c	147	23.3	Air
a c	186	23.3	Air
b c	147	108	Air
a b c	186	108	Air
Star Points:			
T_1V	140	50.2	Vacuum
T_2V	194	50.2	Vacuum
t_1V	165	17.2	Vacuum
t_2V	165	147	Vacuum
T_1A	140	50.2	Air
T_2A	194	50.2	Air
t_1A	165	17.2	Air
t_2A	165	147	Air

(Continued)

*four runs at this condition.

Table LII. Optimum Seeking Experiments for the Post Barrier Heat Treatment Process. (Continued)

Treatment	Variables		
Combination	Temperature (°C)	Time (Minutes)	Environment
Phase "C"			
Center Point (V)*	227	5.9	Vacuum
Center Point (A)*	227	5.9	Air
Cube Points:			
(1)	203	2.7	Vacuum
a	253	2.7	Vacuum
b	203	12.6	Vacuum
a b	253	12.6	Vacuum
c	203	2.7	Air
a c	253	2.7	Air
b c	203	12.6	Air
a b c	253	12.6	Air
Star Points:			
T_1V	194	5.9	Vacuum
T_2V	265	5.9	Vacuum
t_1V	227	2.0	Vacuum
t_2V	227	17.2	Vacuum
T_1A	194	5.9	Air
T_2A	265	5.9	Air
t_1A	227	2.0	Air
t_2A	227	17.2	Air

*four runs at this condition

Table LIII. Average Performance Parameters of
Cells Heat Treated in Air.

Temperature °C	Time Min.	OCV mV	SCC mA	Pmax mW	Eff. %	Fill %	No. of Cells
103	199	473	913	286	3.73	66.2	9
103	930	476	892	280	3.65	65.9	9
118	147	478	793	253	3.30	66.8	9
118	430	466	641	209	2.73	70.1	9
118	430	479	869	282	3.68	67.8	8
118	430	480	720	236	3.08	68.5	9
118	430	459	582	183	2.38	68.3	9
118	1255	471	731	233	3.04	67.8	9
133	133	470	814	264	3.44	68.8	9
133	930	477	916	283	3.70	64.8	9
140	50-1/5	470	954	303	3.95	67.6	8
140	430	461	714	278	297	69.3	9
147	23-1/3	485	851	276	3.60	67.0	8
147	108	453	537	167	2.18	68.7	9
165	50-1/5	476	894	277	3.61	65.1	7
165	50-1/5	473	783	256	3.34	69.2	7
165	50-1/5	468	730	230	3.00	67.4	9
165	50-1/5	471	733	238	3.10	68.4	9
165	147	424	595	160	2.08	63.2	9
186	23-1/3	472	733	241	3.14	69.6	9
186	108	456	584	178	2.33	67.2	9
194	5.9	481	862	277	3.62	67.0	9
194	50.2	443	504	146	1.91	65.4	9
203	2.7	475	868	279	3.64	67.8	8
203	12.6	474	753	246	3.21	69.0	9
203	12.6	473	726	232	3.02	67.5	9
227	2	487	850	287	3.75	69.5	9
227	.5.9	465	951	301	3.93	68.1	9
227	5.9	470	822	252	3.29	65.3	9
227	5.9	468	924	278	3.62	65.1	8
227	5.9	461	720	216	2.82	65.3	7
227	17.2	470	798	255	3.32	67.9	9
253	2.7	468	915	250	3.26	58.4	5
253	12.6	435	705	185	2.42	59.9	9
265	5.9	417	407	103	1.34	60.7	9

Table LIV. Average Performance Parameters of Cells Heat Treated in Vacuum.

Temperature °C	Time Min.	OCV mV	SCC mA	Pmax mW	Eff. %	Fill %	No. of Cells
97	430	471	949	289	3.76	64.6	4
103	199	476	880	278	3.63	66.5	8
103	930	475	893	282	3.68	66.5	6
118	147	471	919	301	3.93	69.6	9
118	430	463	689	224	2.92	70.2	8
118	430	481	879	283	3.67	66.9	8
118	430	470	842	277	3.61	67.5	9
118	430	466	847	261	3.40	66.1	9
118	1255	463	812	255	3.32	67.9	9
133	133	478	897	295	3.84	68.8	8
133	930	478	902	280	3.65	64.9	9
140	50-1/5	479	896	285	3.72	66.4	8
140	430	467	847	266	3.47	67.3	7
147	23-1/3	476	924	300	3.92	68.4	9
147	108	469	867	259	3.38	64.0	9
165	50-1/5	476	898	291	3.79	68.2	8
165	50-1/5	470	774	241	3.15	66.4	7
165	50-1/5	475	897	287	3.74	67.4	9
165	147	475	858	273	3.56	67.2	9
186	23-1/3	471	881	280	3.66	67.7	9
186	108	474	806	260	3.40	68.2	9
194	5.9	469	901	271	3.54	64.1	9
194	50.2	472	722	234	3.06	68.8	8
203	2.7	470	951	292	3.80	65.0	9
203	12.6	472	902	293	3.82	68.9	8
227	2	478	864	278	3.62	69.4	8
227	5.9	477	880	285	3.72	68.6	9
227	5.9	471	930	300	3.91	68.5	7
227	5.9	479	783	248	3.23	66.1	8
227	5.9	475	886	272	3.55	64.7	7
227	17.2	471	929	294	3.83	67.2	9
253	2.7	474	873	283	3.70	68.5	9
253	12.6	482	918	298	3.88	67.4	7
265	5.9	469	870	286	3.73	70.1	9

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